Final Report

A LABORATORY EVALUATION OF THE INFLUENCE OF CRUSHED STONE, AGGREGATE TOP SIZE AND BINDER TYPE ON AETM PROPERTIES

TO: J. F. McLaughlin, Director
Joint Highway Research Project

July 6, 1977
Revised September 1977

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-45M

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The attached Final Report is submitted on the HPR Part II Research Study titled "Design Parameters for Asphalt Treated Bases in Rigid and Flexible Pavement Systems". This Report is titled "A Laboratory Evaluation of the Influence of Crushed Stone, Aggregate Top Size and Binder Type on AETM Properties". It has been authored by Mr. Bradley V. Saxton, Graduate Instructor in Research on our staff under the direction of Professors E. J. Yoder and L. E. Wood.

An earlier Interim Report was also concerned with asphaltic bases under rigid pavements and this report extends the research reported therein by covering the use of crushed limestone aggregate. Continuation of this research with a study of asphaltic bases under flexible pavements is being performed under another research project by the Joint Highway Research Project without use of HPR funds. As a result this is the Final Report on this HPR Study.

The Report is submitted for acceptance with the first Interim Report as fulfillment of the objectives of the approved HPR Research. The Report will also be forwarded to ISHC and FHWA for their review, comment and similar acceptance.

Respectfully submitted,

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16. Abstract

This study reports the findings of a laboratory investigation to determine the effect of selected parameters on asphalt emulsion treated mixtures (AETM). The modified Marshall method developed by Dr. Gadallah was used as the evaluation criteria throughout the study.

The work is divided into three separate phases. The first is an extension of Dr. Gadallah's work to cover crushed limestone aggregate. In this first phase the effects of curing time, aggregate gradation, asphalt emulsion content and moisture added to the dry aggregate on selected mix parameters were investigated. In the second phase a comparison between asphalt cement and asphalt emulsion binders was made for two aggregate types and three asphalt contents. In the last phase a preliminary investigation of testing large size aggregates in samples six inches (15.24 cm) in diameter was evaluated for the effect of sample size, aggregate top size, gradation and asphalt emulsion content.

It was found that only the level of curing, aggregate type and level of binder content had a consistently significant effect on the AETM properties measured by the Marshall test.

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Final Report

A LABORATORY EVALUATION OF THE INFLUENCE OF CRUSHED STONE, AGGREGATE TOP SIZE AND BINDER TYPE ON AETM PROPERTIES

by

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Project No.: C-36-45M

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Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
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and the

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Purdue University
West Lafayette, Indiana
July 6, 1977

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Special thanks is given to Dr. Gadallah for his time, guidance and encouragement during all stages of the study.

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LIST OF SYMBOLS

AETM - Asphalt emulsion treated mixtures

%AE - Asphalt emulsion residue content*

$\%V_A$ - Percent air voids after curing

$\%V_W$ - Percent of voids filled with moisture after curing

$\%V_T$ - Percent total voids = $\%V_A + \%V_W$

%VMA - Percent voids in the mineral ag regate (based on aggregate and mix apparent specific gravities)

G_d - Ovenddry bulk specific gravity of specimen

G_w - Air cured bulk specific gravity of specimen

γ_d - Dry unit weight of specimen

γ_w - Wet unit weight of specimen

%W - Percent initial added moisture content*

$\%WC_o$ - Percent moisture retained in the sample after curing*

%MA - Percent moisture absorbed while soaking*

%TL - Percent total liquid after curing = $\%AE + \%WC_o$

P - Marshall stability

%P - Percent retained stability after the water sensitivity test

F - Marshall flow

%F - Percent retained flow

S_m - Marshall stiffness = P/F

$\%S_m$ - Percent retained stiffness

LIST OF SYMBOLS (Continued)

I_m - Marshall index

$\%I_m$ - Percent retained index

* - Percent by weight of dry aggregate

EXECUTIVE SUMMARY

The findings of a detailed laboratory investigation concerning the effects of asphalt content (asphalt emulsion vs asphalt cement), added moisture content, aggregate gradation, the use of additives (1% portland cement), aggregate types (sand and gravel and crushed stone), sample size (four inches and six inches), and aggregate top size (3/4-inch and 1-1/2 inches) are presented in two reports: A Study of the Design Parameters for Asphalt Emulsion Treated Mixes by Gadallah - 1976 and A Laboratory Evaluation of the Influence of Crushed Stone, Aggregate Top Size and Binder Type on AETM Properties by Saxton - 1977. The attached Final Report on the Study is the latter and it also contains a summary of the other.

One asphalt emulsion type and grade (AE-150) and one asphalt cement (85-100) was used in the study. The design parameters were measured using the Marshall equipment.

The Marshall equipment consisted of a mechanical compaction hammer and an autographic stability apparatus. The stability apparatus used in this investigation is essentially the same as the standard Marshall Equipment but it provides a continuous recording chart for the load (lbs.) versus deformation (0.01" units) throughout the testing range from which stability and flow values can be obtained.

The Gadallah study consisted mainly of two major sections. The first section dealt with establishing a method for preparing and testing asphalt emulsion treated mixtures (AETM) using the Marshall equipment. The AETM were evaluated with emphasis on the coating, workability of the mix, ease of handling of the mix, curing rate and amount of moisture retained in the mixture before and after compaction. Based on these factors, a method for preparing the standard Marshall specimen was developed. In addition, a limited study was conducted to evaluate three different reported methods for water sensitivity tests in order to select an adequate method for AETM.

The second section of the Gadallah study involved an evaluation of the influence of several factors such as asphalt emulsion content, added moisture content, aggregate gradation and the use of portland cement on the performance of AETM. The predetermined methods of specimen preparation and testing procedures formed the basis for this investigation.

The evaluation of AETM properties produced a number of significant results. It must be recognized that the properties of AETM are an outcome of a complex array of factors. Evaluating the mix properties as related to only a single factor is not sufficient. The interaction of these factors influence the behavior and properties of the AETM and have to be considered in the evaluation.

The Gadallah study showed that Marshall Stiffness (determined as the ratio between Marshall Stability and Flow, $S_m = \frac{P}{F}$) and/or Marshall Index (represented by the slope of the linear portion of the load-deformation trace obtained from the autographic Marshall Equipment) could be used, in addition to the conventional design parameters for Marshall method of mix design, to better control the mix properties by setting minimum values for these two parameters.

The experiments showed also that the water sensitivity tests have to be an integral part of the Marshall Design Procedure for AETM. Generally, high stability is obtained at the expense of lowered durability (measured here as the resistance to water damage) especially when using the unsoaked ("dry") Marshall stability trends in the design of AETM. The final design must provide a balance between stability and durability requirements. This would be achieved by controlling and evaluating both the "dry" and soaked properties of the mix with a greater emphasis on the soaked specimen results.

Based on the results of the Gadallah investigation, an outline of the preparation and testing procedures for dry and soaked AETM specimens is presented as well as a recommended evaluation system for asphalt emulsion treated mixtures.

The work by Saxton was divided into three separate phases. The first is an extension of Dr. Gadallah's work to cover crushed limestone aggregate. In this first phase the effects of curing time, aggregate gradation, asphalt emulsion content and moisture added to the dry aggregate on selected mix parameters were investigated. In the second phase a comparison between asphalt cement and asphalt emulsion binders was made for two aggregate types and three asphalt contents. In the last phase a preliminary investigation of testing large size aggregates in samples six inches (15.24 cm) in diameter was evaluated for the effect of sample size, aggregate top size, gradation and asphalt emulsion content.

The binder type had some significance for all of the mixture variables except the air voids. The density and Marshall index variables were affected for the sand and gravel mixes while the Marshall stability and stiffness were only affected for the limestone mixes. The water sensitivity test, conducted on the asphalt cement samples, only had a significant effect on the Marshall stability.

The effect of aggregate type was investigated. This factor had the most consistent effect of all factors investigated. The sand and gravel mixes had values less than limestone mixes for all the variables except sample density.

In the last phase of the Saxton study the effects of sample size and aggregate top size were investigated. The aggregate top size did not affect the Marshall test results. It was difficult to get a direct comparison of the effect of sample size on the Marshall parameters.

The results of this study serve several purposes. It provides the highway engineer with a better understanding of the influence of different factors on the design parameters and properties of asphalt emulsion treated mixtures using Marshall equipment. Further, the results provide additional design parameters that could be used in conjunction with the conventional design parameters for Marshall method of mix design to better control the AETM properties. Finally, the laboratory preparation and testing procedures as well as the recommended evaluation system for AETM would provide an important and practical tool for the design of AETM using Marshall equipment.

CHAPTER 1: INTRODUCTION

In recent years a great deal of interest and study has been given to the development of various types of stabilized materials for use in pavement construction. This may be attributed to increasing traffic volumes, increased loadings due to heavy trucks, and the limitations of suitable aggregate supply. This study reports on the behavior of asphalt emulsion treated mixtures (AETM) when evaluated by the Marshall procedure.

The use of AETM has increased tremendously in the past two decades. From its first uses in patching, surface treatments and road mix it has expanded into all layers of the pavement system: stabilizing subgrade soils and base courses, as hot or cold mix surfacing, in slurry or sand seals and even for sideslope erosion control. This has been precipitated by its apparent economical and environmental benefits. The emulsifying material is simply water, instead of costly and smelly hydrocarbons used for liquid cut-backs. The material can be mixed at ambient temperatures thereby saving both the cost and fuel needed for hot mixes. AETM also eliminates the dust and combustion pollutants resulting from the drying and mixing of the aggregate. The use of asphalt emulsion as a stabilizing agent reduces required layer thicknesses and upgrades substandard materials which conserves, and even extends, our limited supply of acceptable aggregates. In spite of its widespread use, the behavior of AETM has not been sufficiently well understood to enable the development of rational design procedures and criteria. The purpose of

this study was to determine the influence of various mix components so that such a procedure could be developed.

The use of AETM as a stabilized base course material, sometimes referred to as black base, has provided satisfactory service in many projects (15,17).* It has also been shown that treated materials are superior to untreated materials (6,28). However, there are also projects that fail either in sections or in their entirety because of an incomplete understanding and thus an improper use of this material. A study of black bases under CRC pavements in Indiana (15) illustrates this point. The pavement had given satisfactory service until recently, when the heavily traveled portions began to show cracking and pumping distress. Both hot and cold mix bases are used in Indiana but the mix under consideration is a three year old, cold mixed asphalt emulsion base. All sections with a six inch (15.24 cm) base layer gave satisfactory service but some of those four inches (10.16cm) thick did have some failures. A comparison of failed and sound sections revealed slight differences in asphalt content and aggregate gradation. Both of these mix variables were included in the present study.

Outline of the Study

This study is a continuation and extension of the work done by Dr. Gadallah (18). He developed a modified Marshall method, similar to that used by Terrel and Wang (51), for the laboratory preparation of Marshall specimens. These specimens were subjected to curing and/or vacuum saturation before being tested in the autographic Marshall testing equipment (42). The continuous record of stability vs flow was used to form new Marshall parameters that may provide better characterization of the mix. The mix components

*Numbers in parentheses refer to references in the bibliography.

investigated include residue content, aggregate gradation, added moisture, portland cement additive and curing time.

The first phase of this study is a direct extension of Dr. Gadallah's work to a second aggregate type; crushed limestone instead of sand & gravel. All of the mix parameters except the use of additives were investigated in this phase. The results of this work is presented in Chapters 4 and 5.

The second phase of this investigation was a comparison of the asphalt emulsion samples, mixed and tested at room temperature, with standard Marshall asphalt cement samples tested at 140^{o}F (60^{o}C). Only the effects of binder type, aggregate type and asphalt content were investigated. Replicates of the asphalt cement mixes were also subjected to the water sensitivity test. The results of this work are discussed in Chapter 6.

The final phase was a preliminary investigation into the use of specimens 6 inches (15.24 cm) in diameter to test mixes with aggregate topsizes greater than 3/4 inch (1.9 cm). The variables investigated in this section are mold size, aggregate top-size, gradation and asphalt content. The results of this section are presented in Chapters 7 and 8.

Previous Studies Utilizing Marshall Methods

There are several design procedures currently available for the determination of optimum asphalt content. One of the most popular is the Marshall procedure developed by the Corps of Engineers. This test utilizes maximum and minimum criteria derived from field experience and the plots of stability, flow, density and voids with asphalt content to determine an optimum asphalt content for the mix. The stability measures the ability to resist deformation and bear loads while the flow value is a measure of the mix flexibility and plasticity.

Several studies have investigated the Marshall test to determine whether it could be related to more fundamental engineering and material parameters. Goetz and McLaughlin (34) reported that the Marshall test is a partially confined compression test due to the specimen size and shape. McLeod (35) found that this lateral support is variable and depends on mix stability, mix flow or angle of internal friction, the friction between testing head and the specimen and the resistance to shearing. The maximum stability can be correlated to the triaxial test results with 10 psi confining pressure (11). As mentioned, the flow value is proportional to the angle of internal friction (21) and is dependent on asphalt content, voids and specimen thickness (17, 29). The stability is a measure of mix cohesion and is dependent on density and specimen thickness (17, 29). With some initial assumptions Metcalf (36) showed that the Marshall test results could be related to bearing capacity and the unconfined compression test by the following equations:

$$q_u = \frac{P}{100} \left(8 - \frac{(30-F^2)}{20}\right)$$

$$q = \frac{P}{F} \left(\frac{120-F}{100}\right)$$

where

q_u = unconfined compressive strength
q = bearing capacity
P = Marshall stability
F = Marshall flow

These studies show that the Marshall test can be related to more complex tests and ultimately to basic material parameters. On the other hand, the need to refine the Marshall test is also evident. The optimum asphalt

content determined by this test doesn't always correspond to that found by other tests (21,34,5,4). Results of the Marshall laboratory test may even be contrary to results observed in the field performance (52). Actual field cores don't always have the strength or mix characteristics observed in laboratory specimens (4). It was also found that the flow value doesn't show the same pattern as the percent strain at failure (29).

Bituminous mixtures are very complex systems and are not easily characterized. It seems apparent that the Marshall stability and flow values are not sufficient by themselves. Metcalf's bearing equation shows that mixes with a variety of stability and flow values could have the same bearing capacity. Both the Asphalt Institute (2) and AASHO (1) recommend that minimum flow criteria also be used. This would prevent brittle or fatigue failures. Other researchers (8,36,12) suggest that a new parameter, dependent on both stability and flow, be investigated. Brien (8) found that the Marshall stiffness, $S_m = P/F$, provided better correlation with rut depth from 100 passes of a test wheel than the Marshall stability. He suggests that a minimum stiffness criteria be developed for various climatic (temperature) conditions. This term also appears in Metcalf's bearing equation. Krokosky and Chen (27) have shown that the stiffness can be used to characterize the stress relaxation of mixes at ambient temperatures. It can also be used to predict the shift in this pattern for various asphalt contents. This parameter may provide a better control over the viscoelastic behavior of the mix. The stiffness and an associated parameter called the Marshall index are included among the response variables in this study.

Bituminous Treated Materials

Ever since the AASHTO road tests there have been extensive studies conducted on treated materials in order to obtain layer equivalencies for these materials (28,37,19). Actual field tests have shown that there does exist a critical layer thickness which will control rutting and other distress mechanisms (28). This approach may be the simplest for design purposes but it does not show how the various mix components affect its performance. Naturally the addition of bituminous material will reduce thickness requirements. It will increase aggregate resistance and bind the fines until the film thickness begins to separate the grains and provide lubrication (43,38). However the extent of this reduction will be dependent on many factors, especially for liquid asphalts.

Many researchers have investigated the factors affecting asphalt cement stabilized materials (14,20,21,23,37,39,49,50). Some of these factors are asphalt content, penetration and viscosity; aggregate type, gradation and shape; test temperature; rate and method of sample compaction or loading and conditions of the test. It has been found that increased fines increase the VMA and asphalt requirements causing the stability to decrease. However the addition of fillers greatly increases stability and the high temperature viscosity of the asphalt (20,35). Other studies found that aggregate gradation has more of an effect than aggregate shape (30,21). Although test temperature and asphalt penetration may change test results, the selection of optimum asphalt contents is not affected (40). In one study a decrease in test temperature from $100^{\circ}F$ to $77^{\circ}F$ resulted in a three-fold strength increase (43). A field study found that the layer equivalency of this material is greatly affected by the seasonal changes in the pavement structure (28). The complexity and multiplicity of factors affecting this material are readily apparent.

However, the behavior of asphalt cement stabilized mixes has been much more extensively studied and understood than those stabilized with liquid asphalts. In addition to the previous factors the type, amount and method of introducing various volatile components must also be considered. The loss of these components during the curing process has a tremendous influence on mix behavior. These mixes have been shown to provide excellent service as base course layers while providing the benefits discussed previously. A study of 27 projects (17) showed resilient moduli values for cored specimens to range between 900 and 27.2 thousand psi. A regression equation relates this strength to density, asphalt penetration and sand fractions. Failures were attributed to improper curing since most of the mixes were water resistant.

Finn (17) concluded from his work that mix curing would not affect thickness design as long as 95% of the ultimate strength is obtained within two years. Factors that influence curing are aggregate and emulsion types, time of compaction, presence of wind, relative humidity and the addition of additives (7). The rate of strength gain increases as the volatiles are lost thru curing. It has been found that temperature differences between 60°F and 100°F don't affect the rate of curing (50). Even when compacted specimens are placed in plastic bags, so there is no actual loss of moisture, the mixes show an appreciable gain in strength (45). Throughout the early curing period the mix behaves similar to untreated aggregate in that the strength is proportional to the confining pressure (50,51, 21). This relationship is reduced through curing until, as for asphalt cement mixes, the strength is unaffected by confining pressure.

The procedure and type of mixing also affects the rate of curing. Additional moisture may be added to aid

in the distribution of the asphalt or to facilitate compaction. More voids are required to accommodate this moisture (45) and one study (48) found that coating over 50% does not greatly affect mix strength. Several different mixing procedures have been developed with concomitant curing conditions (24, 51, 12, 50). The ultimate or fully cured condition has been represented as 180 days at 68°F (51) and either 3 days at 120°F alone (24) or preceded by 7 days at room temperature (51).

The use of portland cement as both a filler and an additive has shown great effectiveness in overcoming adverse curing conditions or increasing the rate of strength development; with increases as high as 200%. One theory for this is that the cement neutralizes the emulsion's charge allowing the asphalt to coalesce (51). However, additional 'free' water is required for this additive to be effective (24). Even when saturated this mix continues to cure. It is only slightly affected by severe water exposure while plain emulsion mixes have a large strength drop with initial exposure and a continued deterioration with further soaking (49). The use of harder asphalts may reduce this deterioration slightly (24).

Several researchers have studied the behavior of materials stabilized with asphalt cement, asphalt emulsion (with and without portland cement), and cut-back asphalts (45, 50, 21). It was found that tests employing slow rates of loading did not adequately reveal the role played by the binders; especially for the liquid asphalts (32, 23, 47). A modified Marshall method was shown to be satisfactory (23, 24) and did not have to deal with the effect of confinding pressure. These studies have shown that the emulsion mixes will attain strengths equal to asphalt cement mixes after 32 days room cure, or 14 days at 125°F, and may be even stronger after 60 days (45, 50). The asphalt mix performance was strongly dependent on test

temperature but this had little effect on the liquid asphalts. When tested at 70°F one asphalt mix only had twenty percent of its strength at 40°F (50). However the AETM had lower water resistance than the asphalt cement, until the mix had been fully cured. Both mixes showed full recovery of their strength after recuring (45). As already mentioned, the addition of 1% to 3% portland cement nearly eliminates this water sensitivity for AETM (12). Fatigue tests show that the portland cement treated emulsion mixes are least resistant while the asphalt cement mixes are most resistant to fatigue failures (45). This shows that when consideration is given to all mix factors, AETM mixes can perform comparably to asphalt cement mixtures.

Permeability and Water Susceptibility

The foregoing discussion highlights the critical effect of moisture on AETM mixtures. The research on CRC pavements in Indiana (15) showed that the AETM subbase was very sensitive to moisture; either in the mix or from the environment. In none of the field locations could cores of this material be recovered. A large amount of water was observed to drain from under the slab into the shoulder test pit. This exemplifies the problem of providing a permeable drainage layer without decreasing strength. Denser gradations and increased asphalt contents increase strength and resistance to water damage but decrease permeability (44).

Several researchers have studied the permeability characteristics of bituminous mixtures. A study of sand aspahlt mixes (45) showed that they obey Darcy's law where the rate of water flow is proportional to the hydraulic gradient. The type of voids, their size (related to gradation) and bitumen content were found to have the strongest influence on permeability.

A number of methods are currently being used to test the effect of moisture on bituminous treated materials. These include the briquet soaking test, swell test, immersion compression test (soaked four days at 120^{o}F) and the water sensitivity test in which a vacuum is used to draw water through the sides of a specimen to a hole in its center (31). In this study the Asphalt Institute water sensitivity test was used (4). Cured specimens are vacuum saturated and soaked for one day before being tested.

The effect of moisture is a critical problem for AETM mixtures used as base courses because of the frequent exposure to some amount of moisture during the pavement life. Although the mix will regain its strength, the amount of time required will be dependent on the length of exposure. It has also been shown that most of these mixes are actually water resistant (17) so moisture could become trapped in the layer. This would suggest the use of drainage layers in conjunction with these bases. The problem is ameliorated when the material is fully cured. This suggests the use of additives and some degree of precompaction curing.

CHAPTER 2: EQUIPMENT AND MATERIALS

Sample Preparation

The equipment used in the preparation of the Marshall Specimens included ovens, mixers and the mechanical Marshall compactor. The equipment described was used in all phases of the project. Besides the specific equipment mentioned below, the standard laboratory equipment used in measuring, characterizing or controlling materials and samples were employed as necessary. This would include penetrometers, fans, water baths, weigh scales, viscometers and distillation equipment; just to mention a few.

Three main pieces of equipment were used in the preparation of the samples. An eighteen cubic foot (0.5 cubic meter), forced air oven was most often used to heat the mixes. At times this was supplemented by a two cubic foot (0.056 cubic meter), electric oven. The mechanical mixing of the mixtures was accomplished by the use of Hobart rotary mixers with whip attachments. For the samples four inches (10.16 cm) in diameter the N-50 mixer with its five liter bowl was used. Due to the large amount of material required by the specimens six inches (15.24 cm) in diameter, it was necessary to use the A-200 mixer with its twenty-three liter bowl. The mechanical Marshall hammer, shown in Figure 1, was used for compaction. The specimens four inches (10.16 cm) in diameter received fifty blows on each face with a ten pound (4.56 kg) hammer while the six inch (15.24 cm) specimens received sixty-five blows on each face with a twenty-five pound (11.39 kg) hammer.

Figure 1. Marshall Compaction Apparatus

Sample Testing

The apparatus shown in Figure 2 was used to conduct the water saturation test. After the sample was air cured, this test was used to measure the sensitivity of the response variables to the presence of moisture. The samples were vacuum saturated with distilled water and then allowed to soak for one day. The vacuum was supplied by a Welch, one third horsepower vacuum pump. The pressure was regulated to a constant value by the use of a feed-back manometer. After the samples were exposed to the vacuum for one hour, the vacuum was used to draw distilled water into the bottom of the chamger until the samples were completely submerged.

After curing, or vacuum saturation, the samples were tested in the autographic Marshall equipment produced by the Rainhart Company. This device, shown in Figure 3, consists of a testing head and a graphic recorder. The testing head is driven by a one half horsepower motor at the prescribed rate of two inches (5.08 cm) per minute. The testing head is equipped with a load cell which is connected to the graphic recorder to record the Marshall stability. The chart is driven by a motor synchronized with the press head in such a way as to record Marshall flow on the horizontal axis. Three different stability ranges may be used: 0 to 2500 (11.1×10^3 nt) pounds, 0 to 5000 pounds or 0 to 10000 pounds. An example of the recording is shown in Figure 4. For more information, please refer to the operating manual.

Mineral Aggregate

Two types of mineral aggregate were used in this study. The first was a crushed limestone which was obtained from Huntington, Indiana. The second was a sand and gravel obtained from West Lafayette, Indiana. In the first phase of

Figure 2. Vacuum Saturation Apparatus

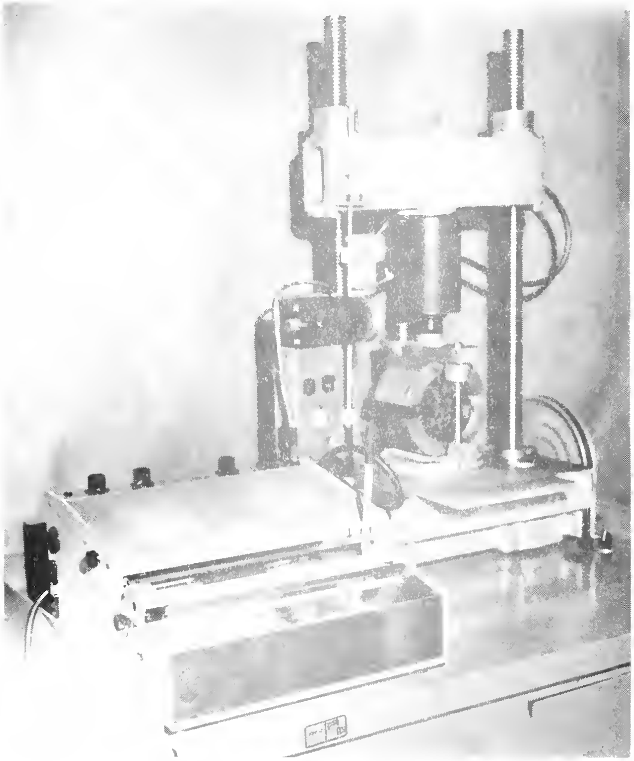

Figure 3. Autographic Marshall Equipment

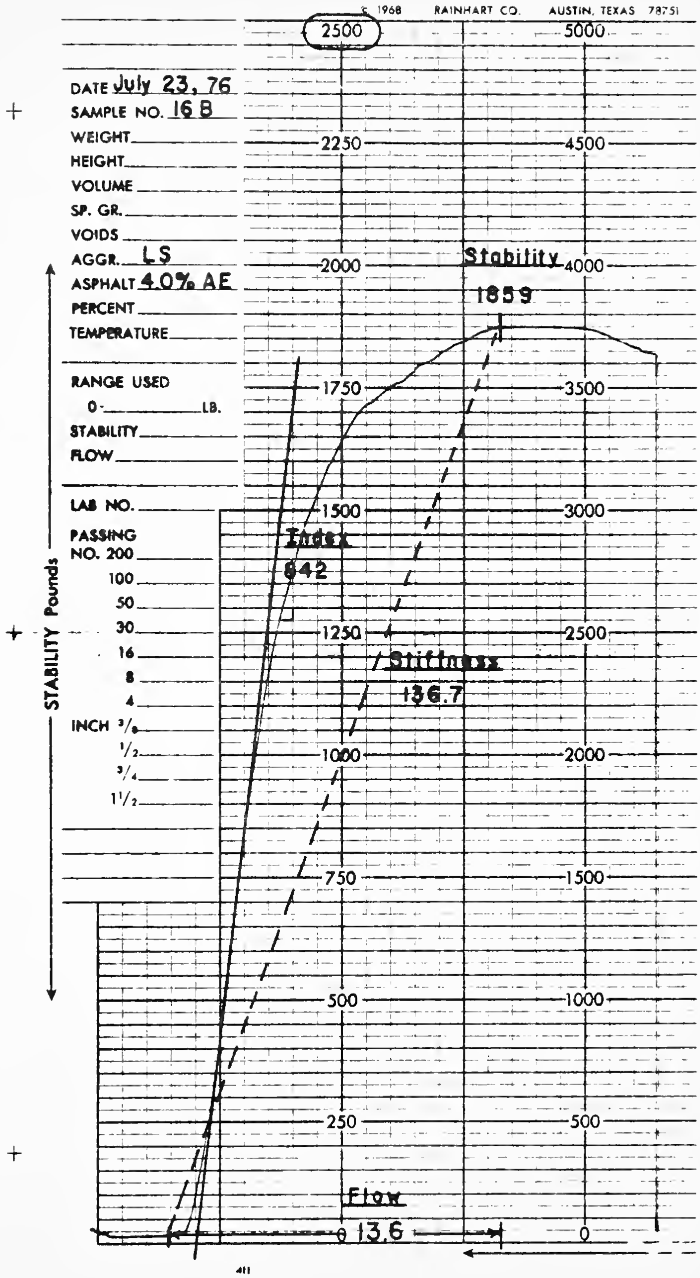

Figure 4. Sample Graph Produced by the Autographic Marshall Equipment

the study the limestone was the only aggregate used while the second and third phases employed both aggregate types equally. (Refer to the experimental design diagrams shown in Figures 7, 33 & 38). The characteristics of the two aggregates will now be described more fully.

The crushed limestone was obtained from the Erie Stone Company in Huntington, Indiana. The quarry is identified as aggregate source No. 58 by the ISHC and source 35-1 by the Geologic Survey. The aggregate was dried for twenty-four hours at 250^{o}F (121^{o}C) before being sieved into the individual size fractions used in the study. The material is a fossiliferious, recrystallized limestone with some sandstone and shale inclusions.

The sand and gravel aggregate was the same material employed in an earlier study (18). This aggregate was supplied by the Western Materials Company, a division of the Medina Aggregate Company, in West Lafayette, Indiana. The quarry is listed as source No. 2132 by the ISHC. This aggregate is a terraced sand and gravel material deposited by the Wabash River. It is composed of approximately two-thirds weathered limestone and dolomite (carbonate) aggregate and one-third noncarbonate aggregate. As much as one-fifth of the latter group is composed of various types of granite.

The aggregates may be further characterized by the measurements presented in the following tables:

Table 1. Aggregate Properties

	Limestone	Sand and Gravel
Bulk Specific Gravity (SSD)	2.696	2.644
Apparent Specific Gravity	2.741	2.710
Absorption, %	1.280	1.560
Mineral Filler, (<#200 sieve) Non-plastic		

Table 2. Sand and Gravel - Percentage of Crushed Particles

Sieve Size	0 Faces	1 Face	2 Faces	3 or More Faces
1½"-1"	58.8	8.8	17.6	14.7
1"-3/4"	52.5	11.9	15.3	20.4
3/4"-3/8"	44.6	4.6	10.8	39.9
3/8"-#4	42.7	9.0	21.3	26.9
Average	49.7	8.6	16.3	25.4

Aggregate Gradations

In the first two phases of the study the ISHC #73-B gradation specification was used. This is the same gradation used previously (18) and is shown graphically in Figure 5. All the material passes the 3/4 inch (1.90 cm) sieve. The specification band is divided into three separate gradations. The fine and midpoint gradations follow the upper limit and middle of the specified band, respectively. To facilitate the handling of samples and mixes the coarse gradation was chosen at the "quarter point", midway between the midpoint and lower limit of the specification band. These gradations were then used to recombine the aggregates into controlled batches during sample preparation.

The third phase uses the ISHC #53-B gradation with a top-size of one and a half inches (3.81 cm). This specification is divided into three gradations as mentioned above; at the upper, mid and quarter points. The gradation is also scalped at the 3/4 inch (1.90 cm) sieve to provide standard Marshall specimens with three quarter inch top size aggregate. The scalped percentage was balanced over the remaining sizes and thus changed the gradation curve as seen in Figure 6. The graph shows that

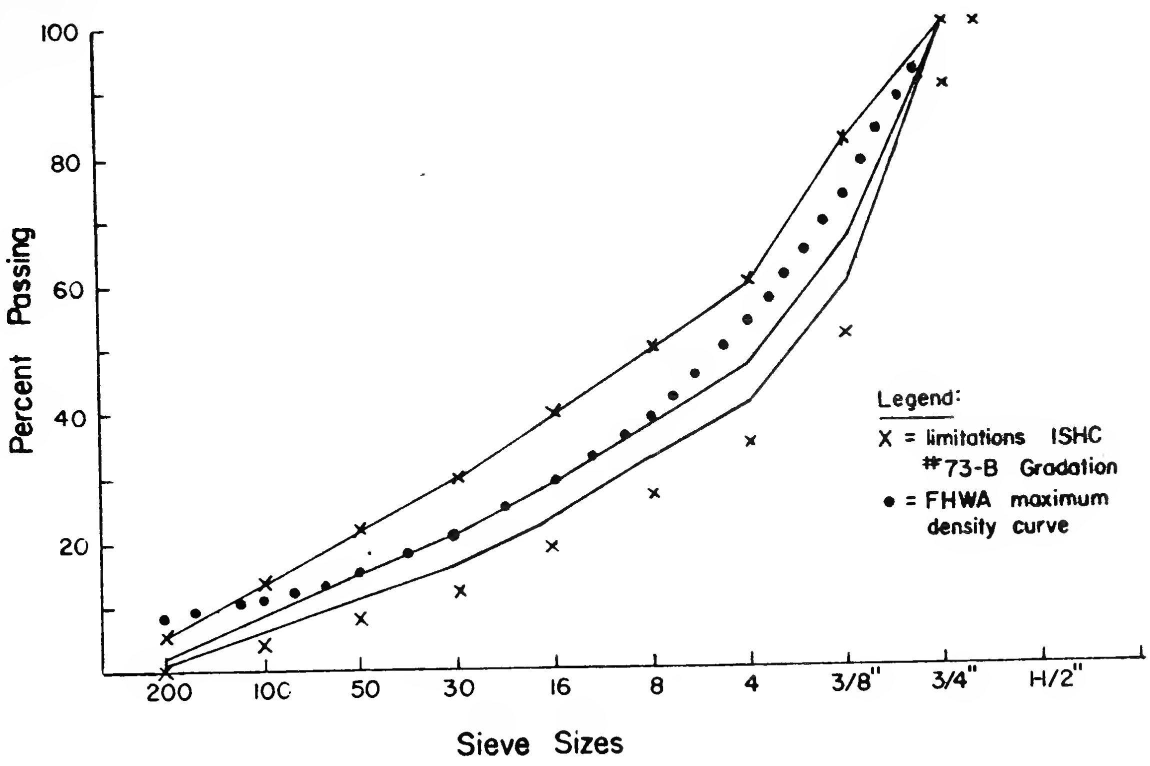

Figure 5. Aggregate Gradations - Phase I & II

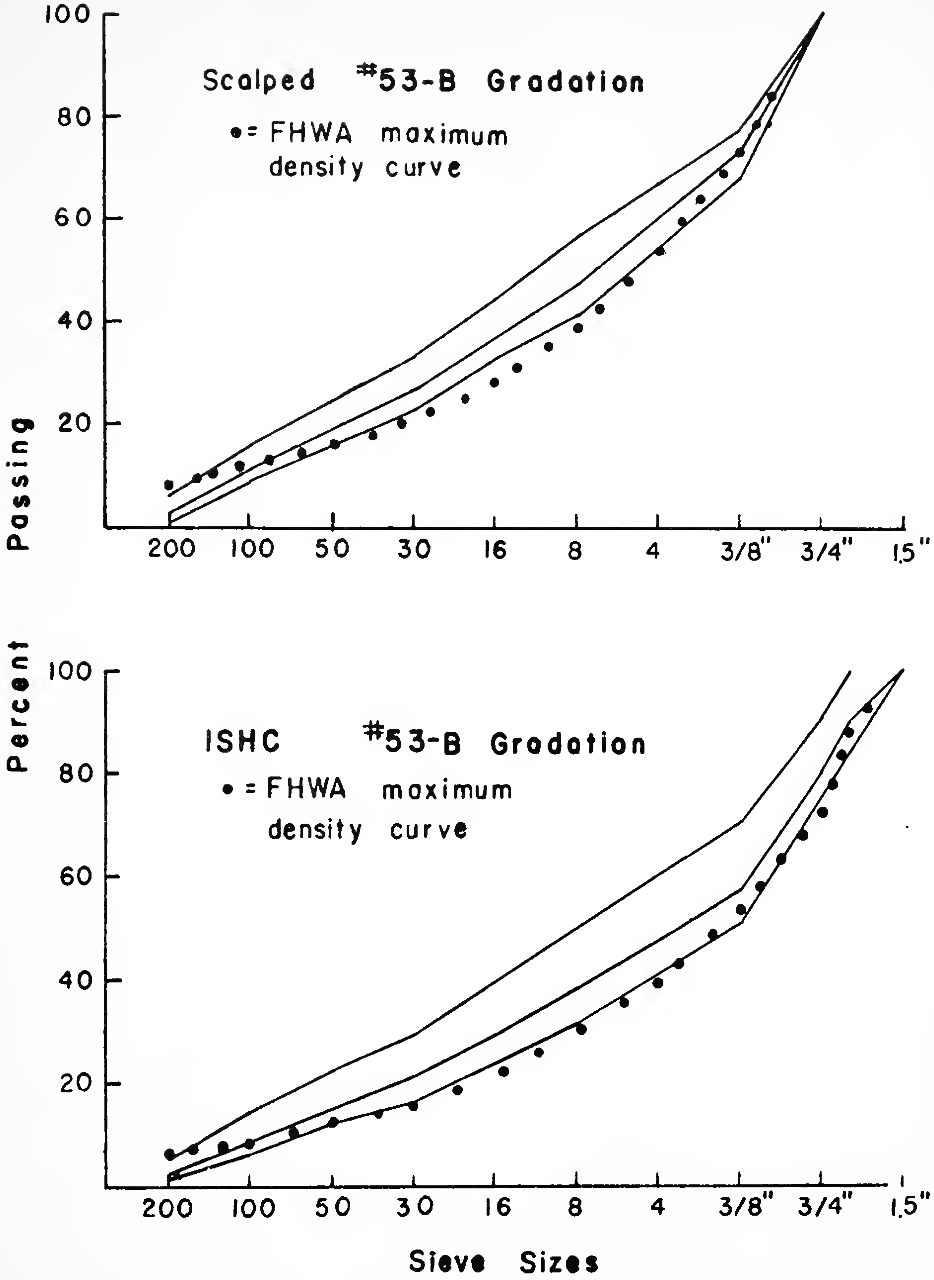

Figure 6. Aggregate Gradations - Phase III

the scalped fine gradation is entirely above the original band and that the other two gradations generally fall between the original fine and midpoint gradations. The coarse gradation seems to lie closest to the maximum density curve in both cases.

Bituminous Materials

The base asphalt used in making the asphalt emulsion was also used as the asphaltic cement material. This is an AP-3 material with a measured penetration of 106 and a specific gravity of 1.003. To obtain the 170 centi-stoke viscosity required by the Marshall method, the asphalt cement had to be heated to nearly 300°F (148.9°C).

This asphalt cement was used to produce the AE-150 mixing grade emulsified asphalt employed throughout the study. The emulsion was formulated and produced by the K. E. McConnaughay Laboratory in Lafayette, Indiana. Two batches of the emulsion were required during the course of the study. Their properties are shown in the following table:

Table 3. Asphalt Emulsion Properties

	Batch I	Batch II
% Residue by Distillation	68.43	67.10
Penetration of residue*	160-200	150-220
Specific gravity of residue (77°)	0.9979	0.9990

*77°F, 5 sec, 100 gm

CHAPTER 3: EXPERIMENTAL DESIGN AND PROCEDURES FOR PHASE I

Introduction

This study is a continuation of the work conducted by Dr. Ahmed Gadallah (18). Consequently the procedures and methods, as well as the level of the variables, he developed were also used in this study. His work was done exclusively with sand and gravel aggregate while this study also uses crushed limestone. This study was also extended to include a section with asphalt cement as the bituminous binder.

The study is divided into three separate phases of work. All phases use the modified Marshall Method for asphalt emulsion treated material (AETM) developed by Dr. Gadallah. This procedure is summarized under experimental procedures. The first phase, also referred to as section one, will be described in this chapter while the second phase will be described in Chapter 6 and the third phase in Chapter 7.

Experimental Design of Phase I

This phase of the study is a direct extension of Dr. Gadallah's work to include crushed limestone aggregate. The independent parameters investigated in this section include gradation, amount of asphalt emulsion residue, amount of moisture added to the dry aggregate, sensitivity of the samples to moisture and the curing time of the compacted samples. The factorial arrangement of these variables and the cells tested are shown in Figure 7.

Gradation	% AE (residue) \ % W Added Moisture / Curing Time	1.5: 1 day 72°F	1.5: 3 day 72°F	1.5: 3 day 120°F	3.0: 1 day 72°F	3.0: 3 day 72°F	3.0: 3 day 120°F
Fine	2.5	Δ	X		Δ	Δ	
	3.25	ΔO	X		ΔO	ΔO	
	4.0		X			Δ	
Midpoint	2.5	X	X	X	X	X	X
	3.25	X	X	X	X	X	X
	4.0	X	X	X	X	X	X
Coarse	2.5		X			Δ	
	3.25	ΔO	X		ΔO	ΔO	
	4.0		X			Δ	

Legend:

X = 3 samples tested 'dry' & 2 samples tested 'soaked'.
O = 2 samples tested 'soaked'.
Δ = 2 samples tested 'dry'.

Figure 7. Experimental Design of Phase I

This first phase of the study was conducted exclusively with crushed limestone aggregate and asphalt emulsion binder. The three aggregate gradations are derived from the #73-B gradation, as described in the section on materials. The two levels of moisture added to the dry aggregate were selected at one and a half and three percent.* All three of the asphalt contents used by Dr. Gadallah were also used in this study. The emulsion residue levels are 2.5, 3.25 and 4.0 percent. Emphasis was placed on the early curing conditions with the one day, three day and the ultimate curing conditions being investigated. These are the independent variables or parameters to be evaluated with respect to their influence on the mix and Marshall response variables.

The analysis of this section will be divided into two parts. In Chapter 4 the midpoint gradation will be used to isolate the effect of the other three parameters. With this as a basis, the effect of gradation will be analyzed in Chapter 5.

Procedures for Sample Preparation

As previously mentioned, all the procedures for AETM preparation used in this study were developed and standardized by Dr. Gadallah. These procedures were used to permit direct comparisons to be made between the two studies. All of the AETM samples used in this study were prepared by the procedure outlined below. Only a few minor changes were required for the preparation of the samples six inches (15.24 cm) in diameter and these will be discussed in Chapter 7.

1. Weigh out the batch weight of dry aggregate according to the gradation specification being used.

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*All asphalt and moisture contents are expressed as a weight percentage of the dry aggregate.

2. Add an initial amount of distilled water to the aggregate and hand-mix thoroughly.
3. Leave the aggregate at room temperature for fifteen minutes.
4. Add the amount of asphalt emulsion needed to provide the specified residue content.
5. The emulsion is distributed by mechanically mixing the batch for not more than two minutes. Thorough distribution was usually obtained in 1 to 1½ minutes. This was followed by a 30 second hand mix. If segregation, clumping or uneven coating occurred, this hand mixing was done in the middle of the mechanical mix period.
6. The batch was then placed in a forced draft oven at 140°F (60°C) for one hour.
7. After this heating period, the mix was remixed for 30 seconds with the mechanical mixer.
8. The standard Marshall drop-hammer compactor was used to apply 50 blows to each face of the sample.
9. Half an hour after compaction the samples were extruded and left to cure.

The three levels of cure used in the study have already been mentioned and are, for the most part, self-explanatory. The one and three day cures consist of leaving the sample at room temperature (68-74°F, 20-23.3°C) for the prescribed period. The samples were placed upon a table covered with absorbent, brown paper and left until tested. For the ultimate condition the samples were placed in an oven at 120°F (48.9°C) for three days. After this cure they were left at room temperature for two to four hours before being tested.

Procedures for Sample Testing

After the samples were cured, two different treatments were used prior to testing. The first treatment was denoted as the "dry" test and the second as the vacuum saturated or "soaked" test. The soaked test is a test developed by the Asphalt Institute to expose the sample to moisture in order to determine its water susceptibility. In both cases the samples are ultimately tested in the autographic Marshall equipment.

The dry test was initiated one hour before the end of the curing period. At this time the specimens' heights were measured and their specific gravities determined by the saturated surface dry test, ASTM D 2726. In the case of the oven cured samples, this procedure was modified to permit the full curing period. Thus they were removed from the oven at the time of test, allowed to cool for two to four hours, and then measured as above.

After being measured, the samples were placed under a fan and turned approximately every ten minutes until tested. Some of the samples were reweighed before being tested to determine the amount of moisture retained from the specific gravity test. This was found to be insignificant.

After testing, the samples were broken apart and placed in an oven for one day at 230°F (110°C). This weight was used as the oven-dry weight in the density calculations.

When the sample was to be vacuum-saturated before testing the following procedure was used. At the time of test the sample height and specific gravity were measured as in the dry tests. The samples were left under the fan for half an hour before being placed in the vacuum chamber (see Figure 2) and subjected to a vacuum of 30 mm Hg for one hour. At the end of this period, distilled water was

slowly drawn into the bottom of the chamber by the vacuum until the samples were submerged at least a half inch below the surface. The vacuum was then released and the sample left to soak for one day. At this time the new saturated surface dry weight was recorded and the sample immediately tested; while still in the saturated condition. Two samples received this treatment while three were tested by the dry procedure.

CHAPTER 4: EFFECT OF CURING,ASPHALT EMULSION AND ADDED MOSITURE ON AETM PROPERTIES

Introduction

This chapter will evaluate the influence of asphalt emulsion residue content, added moisture content and most importantly, the length of the curing period. These three variables have a very important role in controlling the amount of total liquid present in the sample. The remaining variable investigated in this phase of the study, aggregate gradation, will be discussed in the next chapter. Besides the direct effect of each variable, the interactions between them will also be evaluated. This is important because the loss of moisture during the curing process affects the performance of the asphalt emulsion binder.

The levels of the variables and their factorial arrangement are shown in Figure 8. This is obtained from the complete experiment, shown in Figure 7, by considering only the midpoint gradation. All levels of the other variables are included to produce the eighteen cell, complete factorial design shown. There are three levels of asphalt emulsion, three levels of curing and two levels of added moisture.

In general the midpoint gradation showed the most consistency with regards to the influence of the independent parameters. Thus the trends established in this chapter will form the groundwork for succeeding evaluations. This behavior may be a result of the midpoint gradation most nearly approximating the maximum density curve.

Curing Time	% W Added Moisture	Gradation: Midpoint Gradation		
		% AE (residue)		
		2.5	3.25	4.0
ONE DAY	1.5	X	X	X
	3.0	X	X	X
THREE DAYS	1.5	X	X	X
	3.0	X	X	X
ULT. COND.	1.5	X	X	X
	3.0	X	X	X

Legend :

X = 3 samples tested air dry & 2 samples tested vacuum saturated

Figure 8. Factorial Design to Study the Variables Influencing Total Liquid Content

Analysis of Results

The following analysis of variance model can be used to investigate the AETM response variables:

$$Y_{ijk\ell} = \mu + C_i + A_j + AC_{ij} + W_k + CW_{ik} + AW_{jk}$$

$$+ CAW_{ijk} + \varepsilon_{(ijk)\ell}$$

where $Y_{ijk\ell}$ = measured or response variable

μ = overall true mean

C_i = true effect of curing time

A_j = true effect of the asphalt emulsion residue, % AE

W_k = true effect of added moisture content, %W

$\varepsilon_{(ijk)\ell}$ = true random error, NID$(0,\sigma^2)$

The other terms are interaction effects between the main factors. As already mentioned the subscripts can have the following values;

i = 1,2,3

j = 1,2,3

k = 1,2

ℓ = 1,2 or 3 (3 for the dry tests, 2 for the soaked tests)

The orginal data for the midpoint gradation was tested for homogeneity of variance and normality. These are the two main assumptions needed for an ANOVA analysis. The homogeneity test results are shown in Table 4, for both the dry and soaked tests. For the dry tests only the Marshall index did not have homogeneity of variance. The transformation used to correct this condition was the common logarithm. Of the soaked test variables the Marshall Index and the moisture variables, $\%WC_o$ and V_w, did not show homogeneity of variance. The logarithmic transformation was again used for the Marshall Index while the inverse transformation was required to correct the moisture variables.

Table 4: Results of Phase I Homogeneity Test*
(midpoint gradation)

Response Variables	Dry Test		Soaked Test	
	18 Samples, 2 d.o.f.**		18 Samples, 1 d.o.f.	
	1.) $Q_{2,18,0.001} = 0.228$ 2.) $Q_{2,18,0.10} = 0.173$		3.) $Q_{1,18,0.001} = 0.409$ 4.) $Q_{1,18,0.01} = 0.304$	
	Q Statistic	Homogeneity	Q Statistic	Homogeneity
G_d	0.150	Accept Q_2	0.280	Accept Q_4
G_w	0.162	Accept Q_2	0.157	Accept Q_4
$\%WC_o$	0.158	Accept Q_2	0.531	Reject Q_3
P	0.111	Accept Q_2	0.239	Accept Q_4
F	0.126	Accept Q_2	0.205	Accept Q_4
S_m	0.157	Accept Q_2	0.153	Accept Q_4
I_m	0.342	Reject Q_1	0.433	Reject Q_3
$\log I_m$	0.184	Accept Q_1	0.147	Accept Q_4
V_w	0.152	Accept Q_2	0.526	Reject Q_3
V_A	0.144	Accept Q_2	0.312	Accept Q_4
V_T	0.149	Accept Q_2	0.233	Accept Q_3
VMA	0.149	Accept Q_2	0.228	Accept Q_3
$\%WC_o^{-1}$	-		0.277	Accept Q_3
$\%V_w$	-		0.276	Accept Q_3

*Foster Burr Q test for Homogeneity of Variances

**Degrees of Freedom

The normality of the homogeneous variables was checked by constructing a normality plot. In all cases the variables showed a good linear fit so no further tests were conducted.

The results of the ANOVA analysis are shown in Tables 5 and 6. In general the effect of added moisture does not seem to have a significant effect on the variables investigated. The amount of cure has the largest and most important effect while the AE residue content had a significant but secondary effect. The interactions of the three variables were significant only for the dry tests and did not show any obvious pattern. These results will now be reviewed in more detail by discussing each of the variables separately.

The first response variables to be described are fundamental properties of the samples themselves. These include the air-cured and oven dry densities, the percent air voids, the percent total voids and the percent of voids in the mineral aggregate. Any trends or aberations in these variables would also be reflected, to some extent in the main Marshall parameters. Table A1 shows the value ranges for all the variables investigated as a function of their most important parameter, curing time.

Sample Density

The first variable to be discussed is the sample density. Two measures of this variable were made, one at the end of the curing period and one with the sample oven dried to remove all moisture. The former is referred to as the cured, or wet density and the latter as the dry density. The wet densities are plotted in Figures 9 and 10. The dry densities show the same trends as the wet densities but at a slightly lower value. The correlation co-efficient between the two densities is 0.934.

Table 5: Summary of ANOVA Results for the Dry Test (midpoint gradation)

Source of Variation	Response Variables											
	Y_D	Y_W	WC_o	V_w	V_A	V_T	VMA	P	F	S_M	I_m	$Log(I_m)$
A	S-	S-	S-	S-	S-	S-	S-	S-	S-	S-	S	S-
C	S	S-	S-	S-	S-	S	S	S-	S-	S-	S	S-
W	NS	NS	S-	S-	S	NS	NS	S-	NS	NS	S-	S-
AC	NS	NS	S-	S-	S	NS	NS	S-	NS	NS	S-	S-
CW	NS	S+	S-	S-	S-	NS	NS	S-	NS	S+	S-	S-
AW	S-	S	NS	NS	S	S-	S-	NS	NS	NS	NS	S+
ACW	S	S	NS	NS	S	S	S	S-	NS	NS	S-	S-
Multiple R^2	.785	.870	.940	.940	.963	.949	.247	.933	.526	.634	.221	.456

Symbol	α Level
S-	$0 < \alpha \leq .009$
S	$.009 < o \leq .05$
S+	$.05 < \alpha < .1$
NS	not significant

Table 6: Summary of ANOVA Results for the Soaked Test (midpoint gradation)

Response Variable	A	C	W	AC	CW*	Multiple R^2
γ_D	S-	NS	NS	NS	NS	.628
γ_W	S-	S-	NS	NS	S	.861
WC_o	NS	S-	NS	NS	NS	.460
WC_o^{-1}	S-	S-	NS	S-	NS	.721
V_W	NS	S-	NS	NS	NS	.477
V_W^{-1}	S-	S-	NS	S-	NS	.719
V_A	S-	S-	NS	NS	NS	.799
V_T	S-	NS	S	NS	S	.842
VMA	S-	S+	S	NS	S	.313
P	NS	S-	NS	NS	NS	.873
F	S	S-	NS	NS	NS	.348
S_m	S-	S-	NS	NS	NS	.638
I_m	S-	S-	NS	NS	NS	.844
$\log(I_m)$	S-	S-	NS	NS	NS	.834

*All other terms are NS

Symbol	α Level
S-	$0 < \alpha \leq .009$
S	$.009 < \alpha \leq .05$
S+	$.05 < \alpha < .1$
NS	not significant

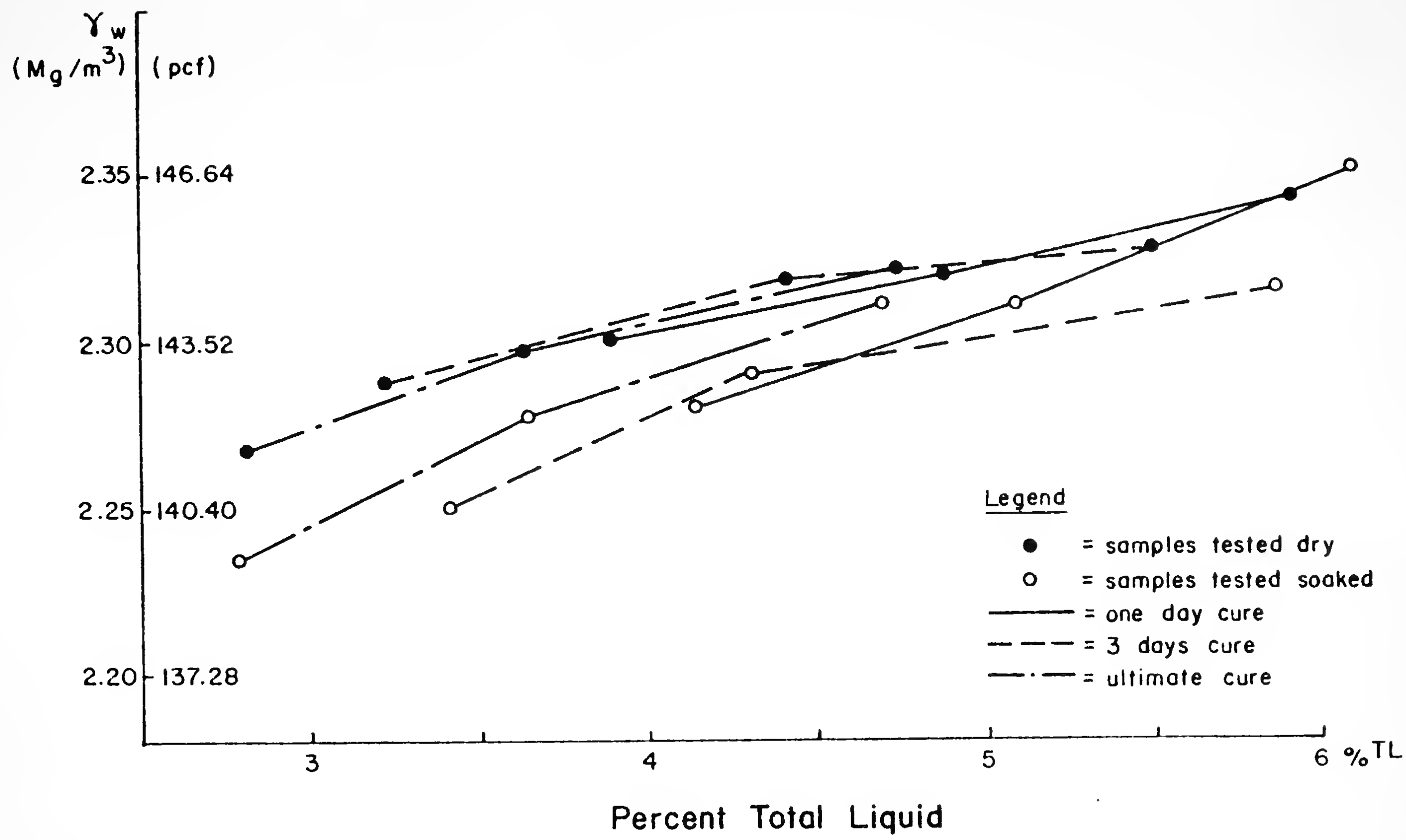

Figure 9. Sample Density for Dry and Soaked Specimens as a Function of Cure and Total Liquid (Midpoint Gradation, 1.5% Added Moisture)

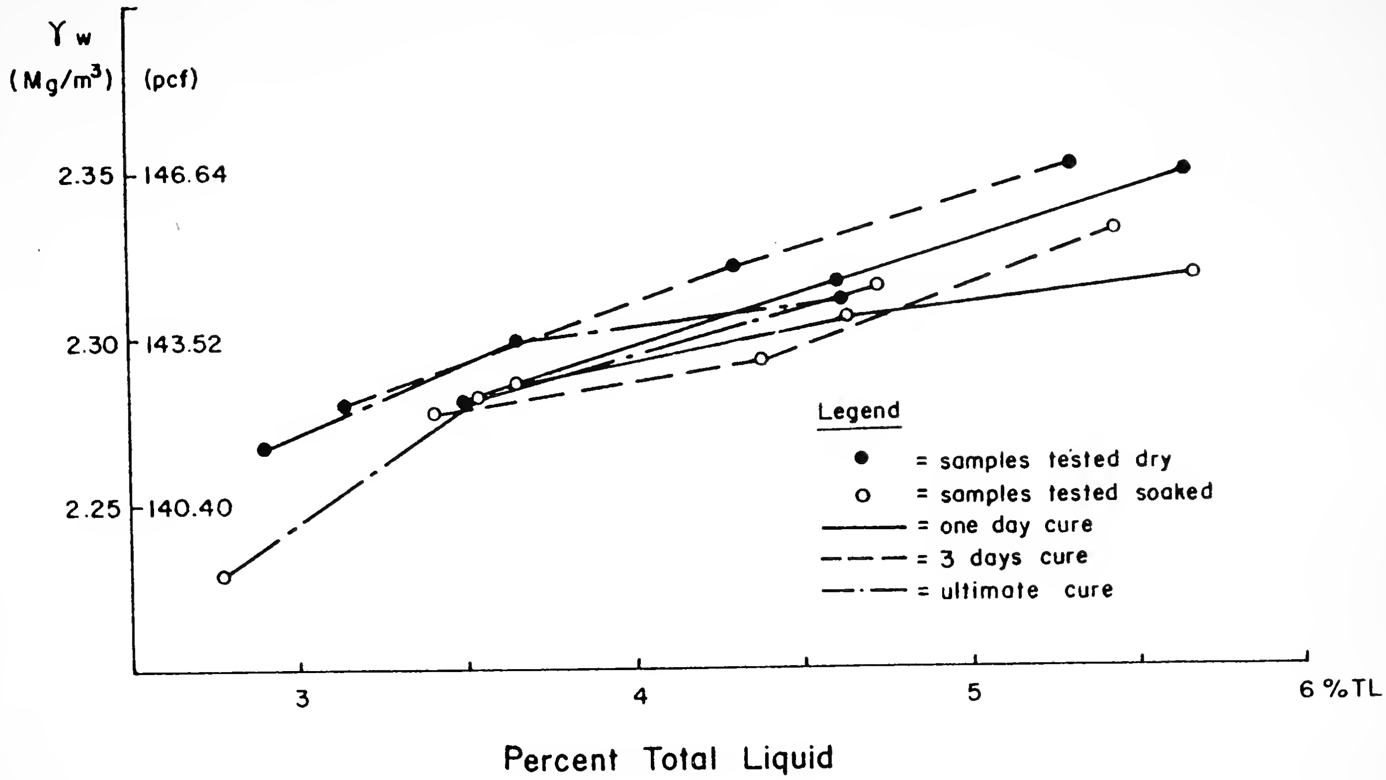

Figure 10. Sample Density for Dry and Soaked Specimens as a Function of Cure and Total Liquid (Midpoint Gradation, 3.0% Added Moisture)

The ANOVA results for the two densities are the same except for the vacuum soaked samples. For these samples the curing parameter and its interaction with added moisture are not significant for the drying density but are significant for the wet density. This is logical because the samples were of uniform volume so, after drying only the content should affect the density. The effect of cure on the dry densities for the dry test is shown to be significant but closer inspection shows that this significance is only for a few isolated cases.

The analysis shows that only the curing and AE residue content factors affected the wet density. The amount of added moisture did not affect the densities. The increased density obtained with higher asphalt contents was significant for all of the cases under consideration. The decrease in density resulting from longer cures was significant for all of the mixes except those with 1.5% added moisture and 2.5% AE residue. This change in density results from a loss of moisture during the curing process as shown in the figures. It can also be seen that this effect increases slightly with available moisture; either from added moisture or from the emulsion.

The samples to be tested in the water sensitivity test have consistently lower densities than those tested dry. However, they show the same trends and the difference is not generally significant. It may be due to the averaging of two, instead of three, sample replicates for this test.

Air Voids

The second variable investigated is the percentage of air voids present in the sample after the curing process. The ANOVA analysis is very different for the two types of tests although the graphs show nearly identical trends. For the dry test all the factors and their interactions are significant. The multiple R^2 value for this test is

0.963. For the saturation test only the AE residue and curing factors are significant while the R^2 value drops to 0.799.

The plots of air voids vs total liquid are presented in Figures 11 and 12. As expected, the air voids decrease with increasing total liquid in a nearly linear manner. Thus all the parameters affecting the total liquid content have an important role in controlling the amount of air voids in the sample. As was already mentioned, the percent added moisture has very little effect. It increases the total liquid slightly for the early curing conditions but otherwise there is no difference. A close look at the dry test shows that the added moisture is significant for only two cases: the one day cure with 2.5% AE residue and the three day cure with 4.0% AE residue.

Thus the AE residue content and curing times are also the most important factors affecting air voids. The two factors have essentially equal importance for the samples with 3.0 percent added moisture but those with 1.5 percent show the AE residue content to be much more significant. It can be seen that the air voids are highly correlated with sample density and exhibit trends exactly the reverse of those shown by the sample density. Thus the samples to be tested saturated show an insignificantly higher void content due to their lower densities.

Total Voids

The total voids are composed of both air and water voids. Thus the effect of moisture might be expected to be greater for this variable. However a loss of moisture is compensated for by an increase in air voids and there is no change in the amount of total voids. The analysis shows that only the AE residue content consistently affects this variable.

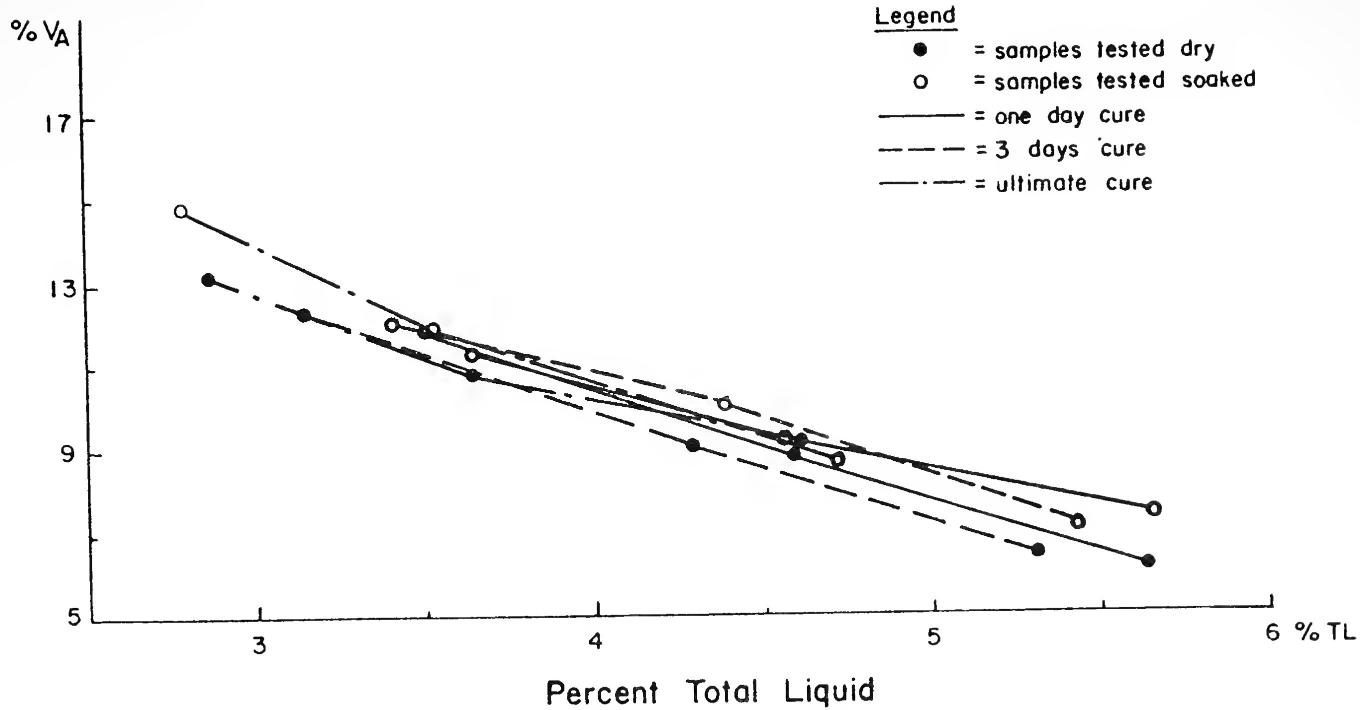

Figure 11. Percent Air Voids for Dry and Soaked Specimens as a Function of Cure and Total Liquid (Midpoint Gradation, 1.5% Added Moisture)

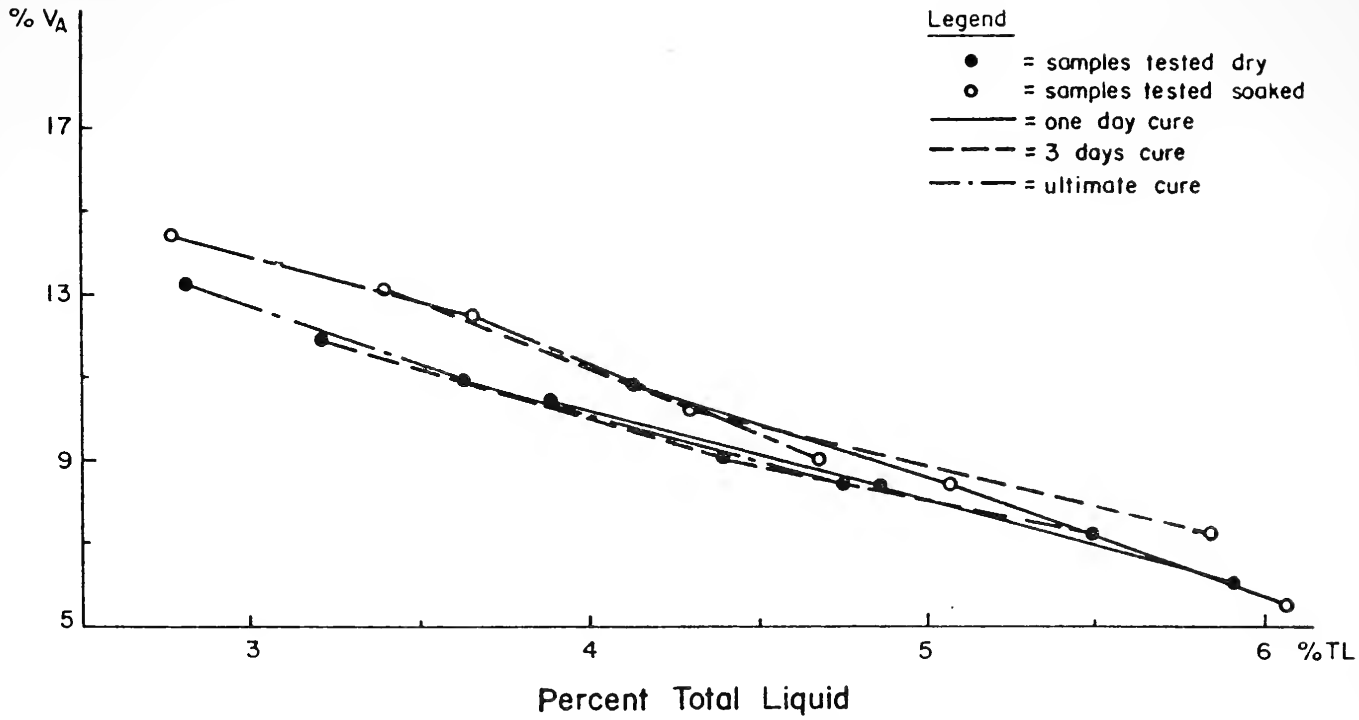

Figure 12. Percent Air Voids for Dry and Soaked Specimens as a Function of Cure and Total Liquid (Midpoint Gradation, 3.0% Added Moisture)

The ANOVA results for this variable must be examined very closely. The significance of cure for the dry test was found to represent a single case: the three day cure with 1.5% added moisture and 4.0% AE residue. The only other significant terms contain the AE residue variable. For the samples to be tested saturated, the percent added moisture and its interaction with cure are also shown to be significant. This can be attributed to a high void content for the three day cure with 3% added moisture and for the one day cure with 4.0% residue and 1.5% added moisture. Although these trends would be expected from the sample density results, neither the significance of this variable nor the scatter observed for the samples with 3.0% added moisture would have been anticipated.

The results are plotted as a function of total liquid content in Figures 13 and 14. For each type of test the total voids are generally constant for any asphalt content. The only effect of curing is to decrease the moisture and thus shift the curve to the left. In all cases there is the ordering of ultimate cure followed by the three day cure and finally the one day cure.

The effect of added moisture is again rather limited and corresponds to that shown by the densities except for the samples with 3% added moisture. These mixes have more available moisture and show a large shift of the curves since they retain more moisture and thus have a higher total liquid content. This effect is reduced through the curing process until, as shown by the ultimate cure for the dry test, there is no difference observed at any of the AE residue levels.

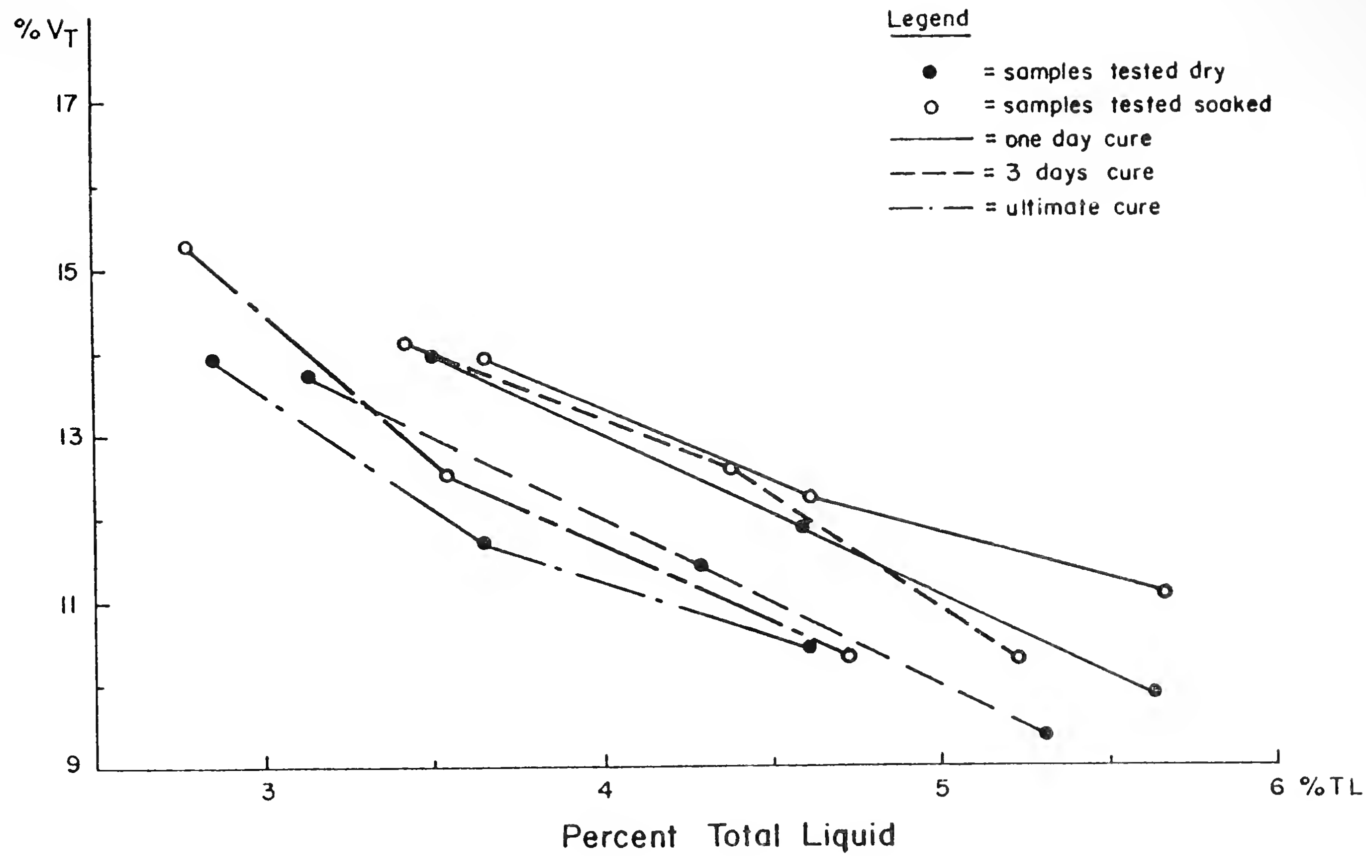

Figure 13. Percent Total Voids for Dry and Soaked Specimens as a Function of Cure and Total Liquid (Midpoint Gradation, 1.5% Added Moisture)

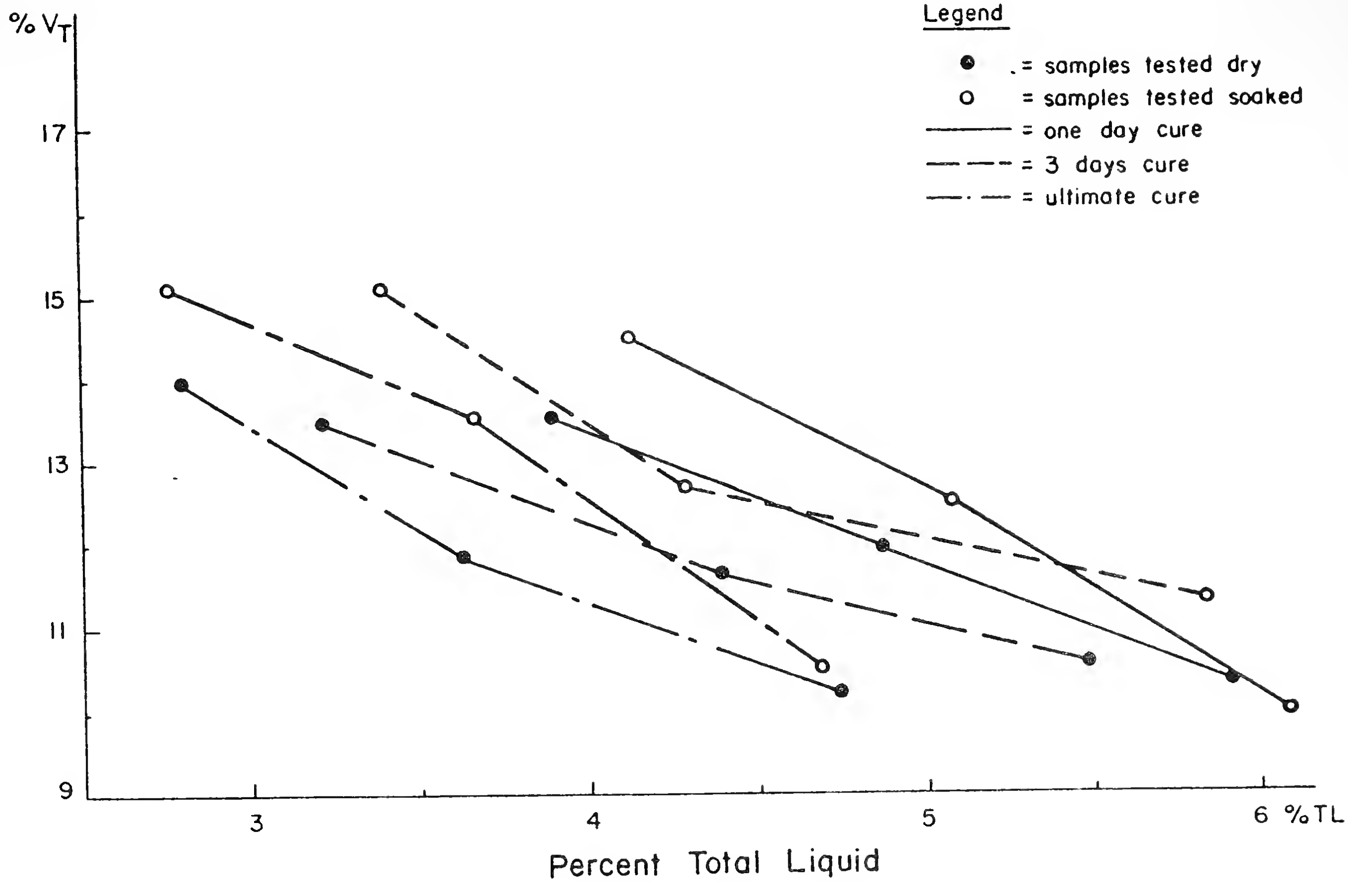

Figure 14. Percent Total Voids for Dry and Soaked Specimens as a Function of Cure and Total Liquid (Midpoint Gradation, 3.0% Added Moisture)

Voids in the Mineral Aggregate

The last of the void variables to be investigated in the voids in the mineral aggregate. In the standard Marshall method these voids would be expected to decrease with an increase in asphalt until the optimum is reached. As shown in Figure 15, this is the general trend for all but the dry tests with 3% added moisture. These mixes show a constant VMA for all AE residue and cure levels. However the statistical analysis shows that this decrease is only significant for the samples with 3 days cure, 1.5% added moisture and tested dry. It should be noted that these voids give a better indication of mix compactability than do the density results alone. This can be seen by the upswing in voids for those cases showing only a slight leveling off in their densities.

The ANOVA analysis also shows the added moisture variable to be significant for the samples tested saturated and the curing variable to be significant for both types of test. However, the plots and a pairwise comparison of the results show that neither of these factors are generally significant.

Percent Retained Moisture

The percent retained moisture is directly correlated to the amount of water voids present in the mix and is also a measure of the effectiveness of the curing process. The ANOVA results show that curing and asphalt content were significant for the transformed values of the soaked test while all but two of the interaction terms were significant for those to be tested dry.

The results show a linear increase with increased AE residue content as shown in Figure 16. There is a significant difference in moisture between all of the curing levels but only for the one day cure tested dry does the amount of added moisture become significant. For the one day cure

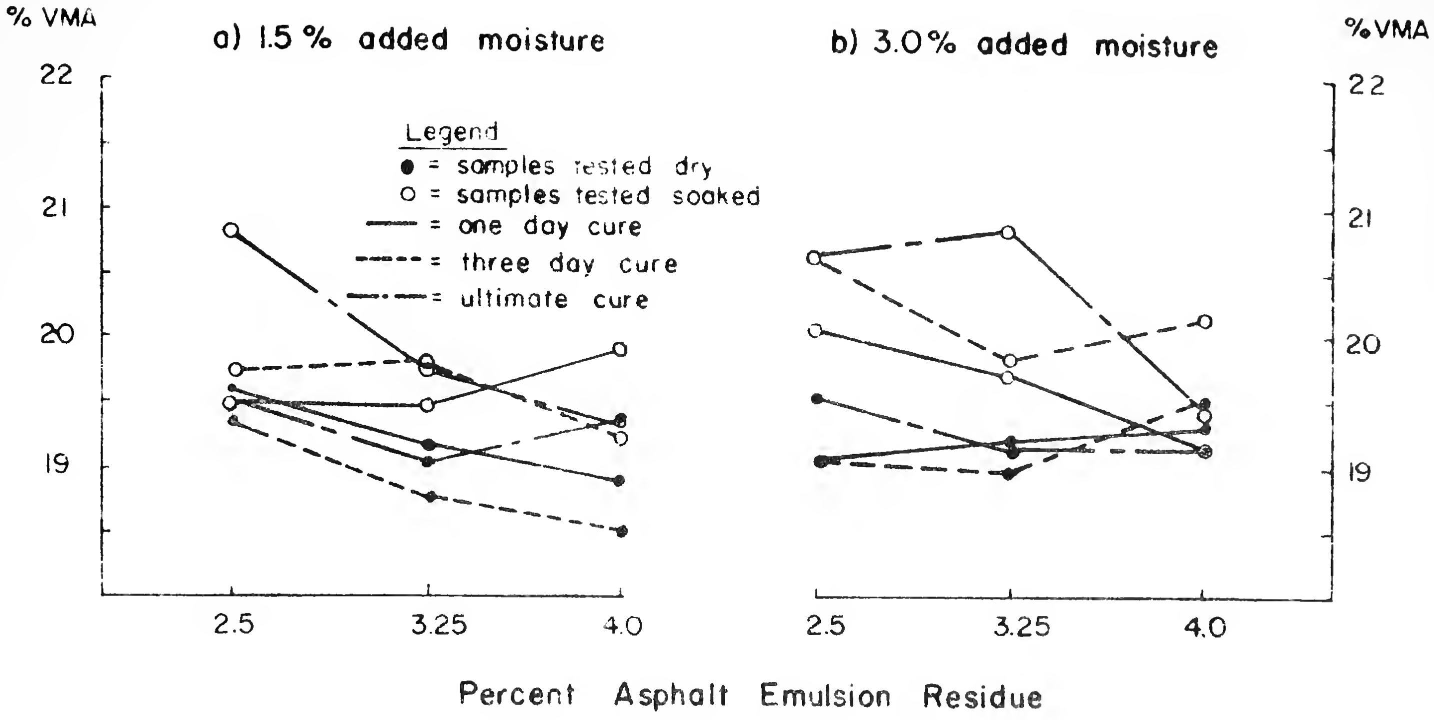

Figure 15. Percent VMA for Dry and Soaked Specimens as a Function of Cure and AE Residue Content (Midpoint Gradation)

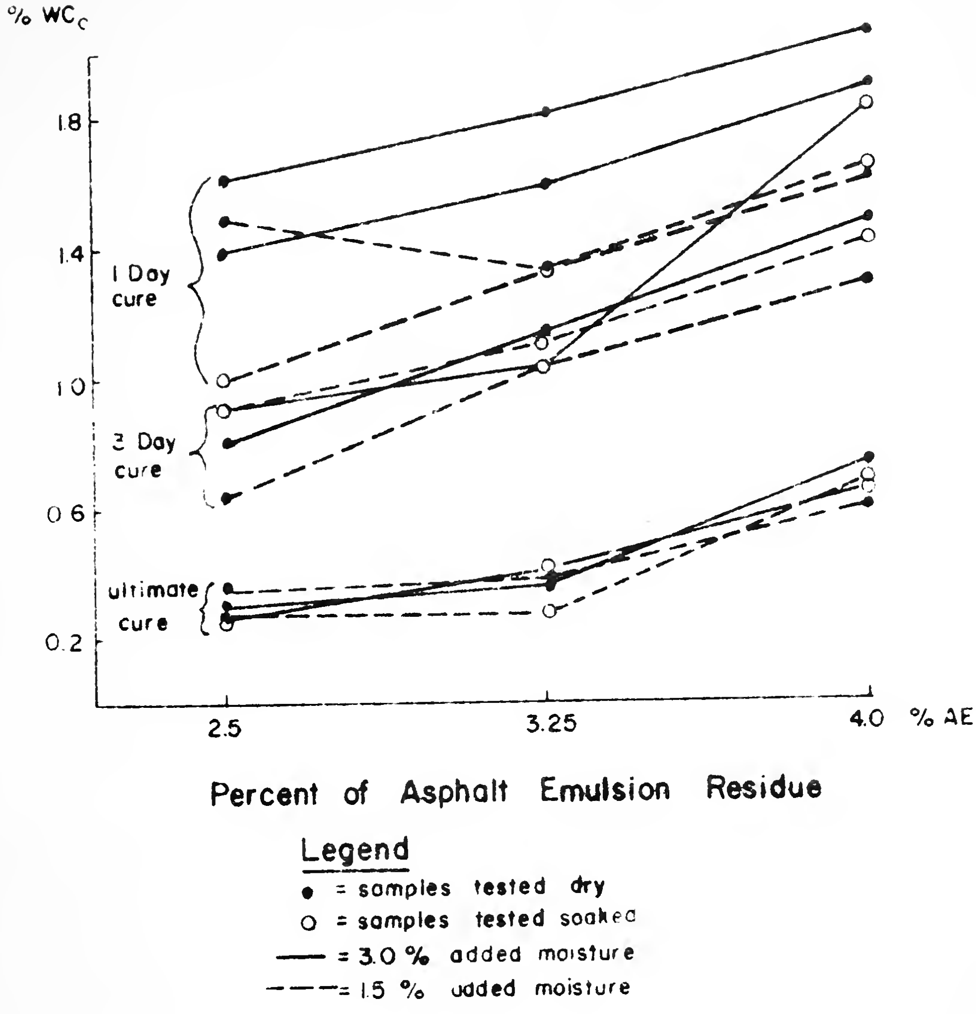

Figure 16. Percent Moisture Retained after Curing as a Function of Cure and AE Residue Content (Mid-point Gradation)

there also is more variation between replicates showing that control of the moisture during sample preparation is variable.

Moisture Absorbed in Soaking

The last of the sample characteristics to be discussed is the amount of moisture absorbed by the samples during the water sensitivity test. The results are plotted in Figure 17 for the two levels of added moisture. As expected, the moisture has filled a portion of the available (air) voids and consequently resembles this variable. The one day cure has the fewest available voids so it shows the least absorption while the ultimate cure shows the highest. The effect of added moisture is only to slightly increase the variation between cures for the samples with the higher added mo sture level. The most important factor is the AE residue content which causes a linear decrease in absorption with increased AE residue contents.

Marshall Stability

The first of the independent Marshall variables to be analysed is the Marshall Stability. This mix variable is a measure of strength or resistance to load. The ANOVA analysis shows that only the interaction of AE residue and added moisture is not significant for the dry test. However the only significant factor in the saturated test is curing. To understand these results a visual examination of the data is required.

The results are presented graphically in Figures 18 and 19. The first item to be noted is the clearly dominant effect of the length of curing. Except for the samples tested dry with 2.5% AE residue, there is not a significant difference between the one and three day cures, although in all but one case there is some increase in stability. However, there is a very marked increase with the ultimate

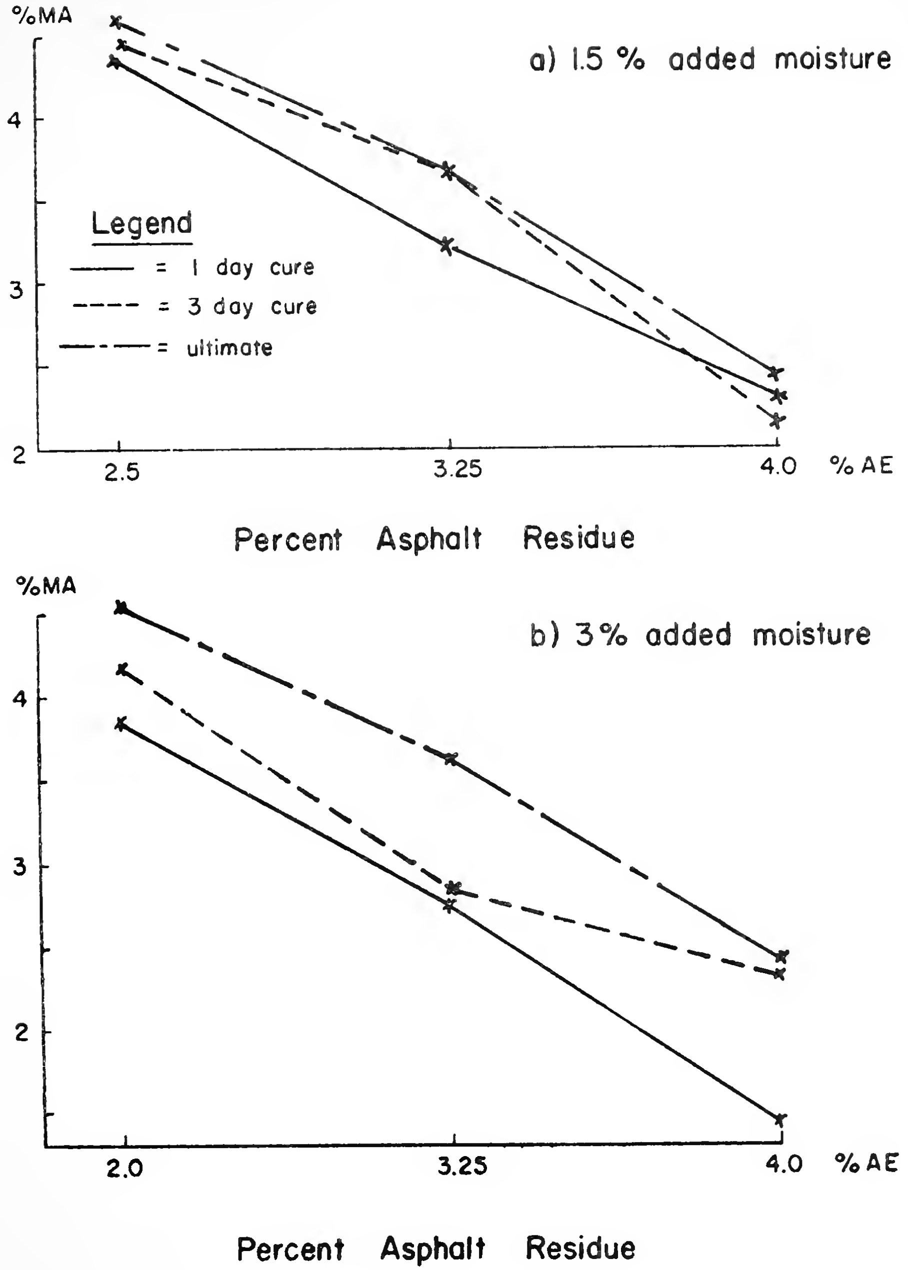

Figure 17. Moisture Absorbed in Soaking as a Function of Curing and AE Residue Content (Midpoint Gradation)

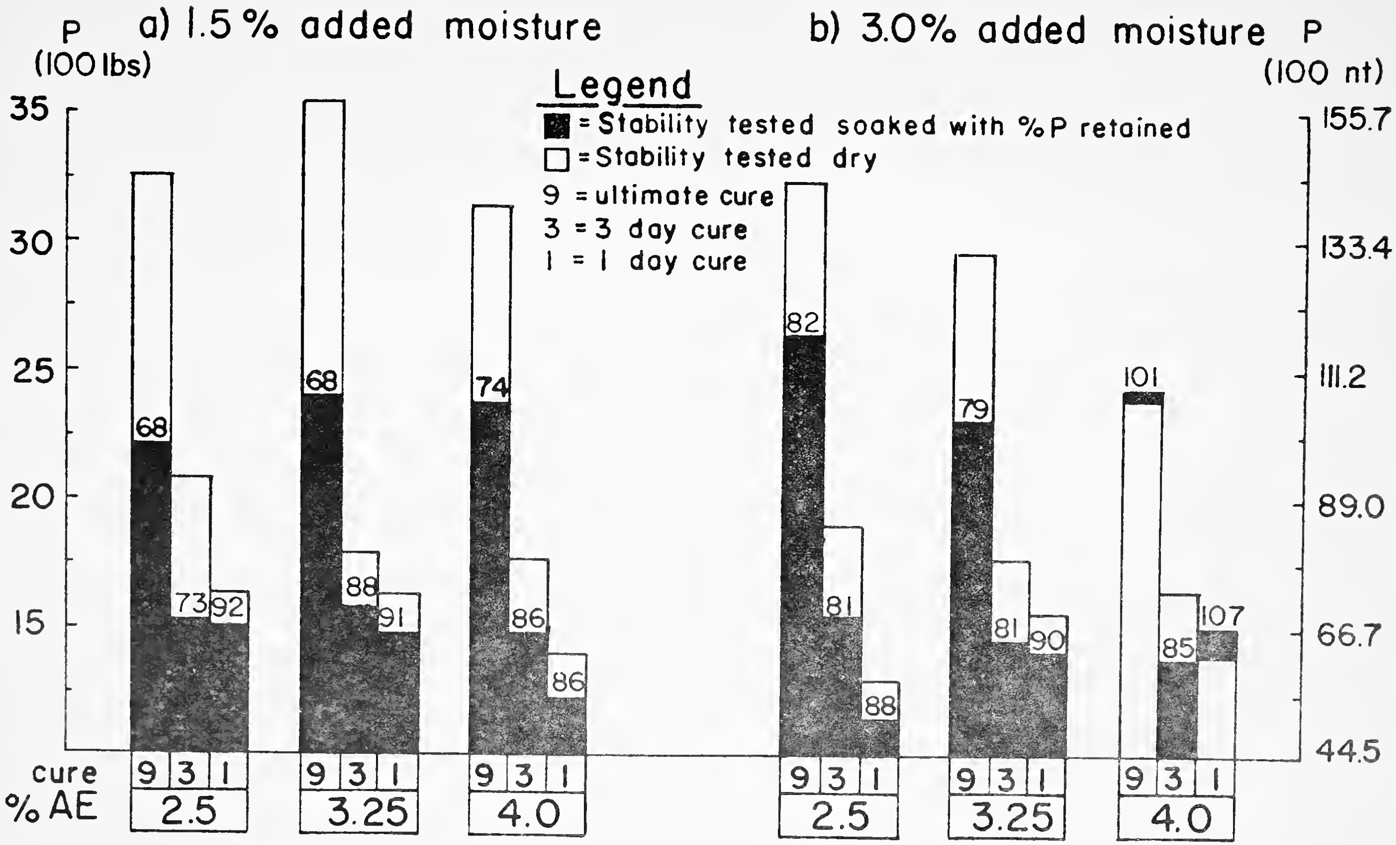

Figure 18. Marshall Stability for Dry and Soaked Specimens as a Function of Curing and AE Residue Content (Midpoint Gradation)

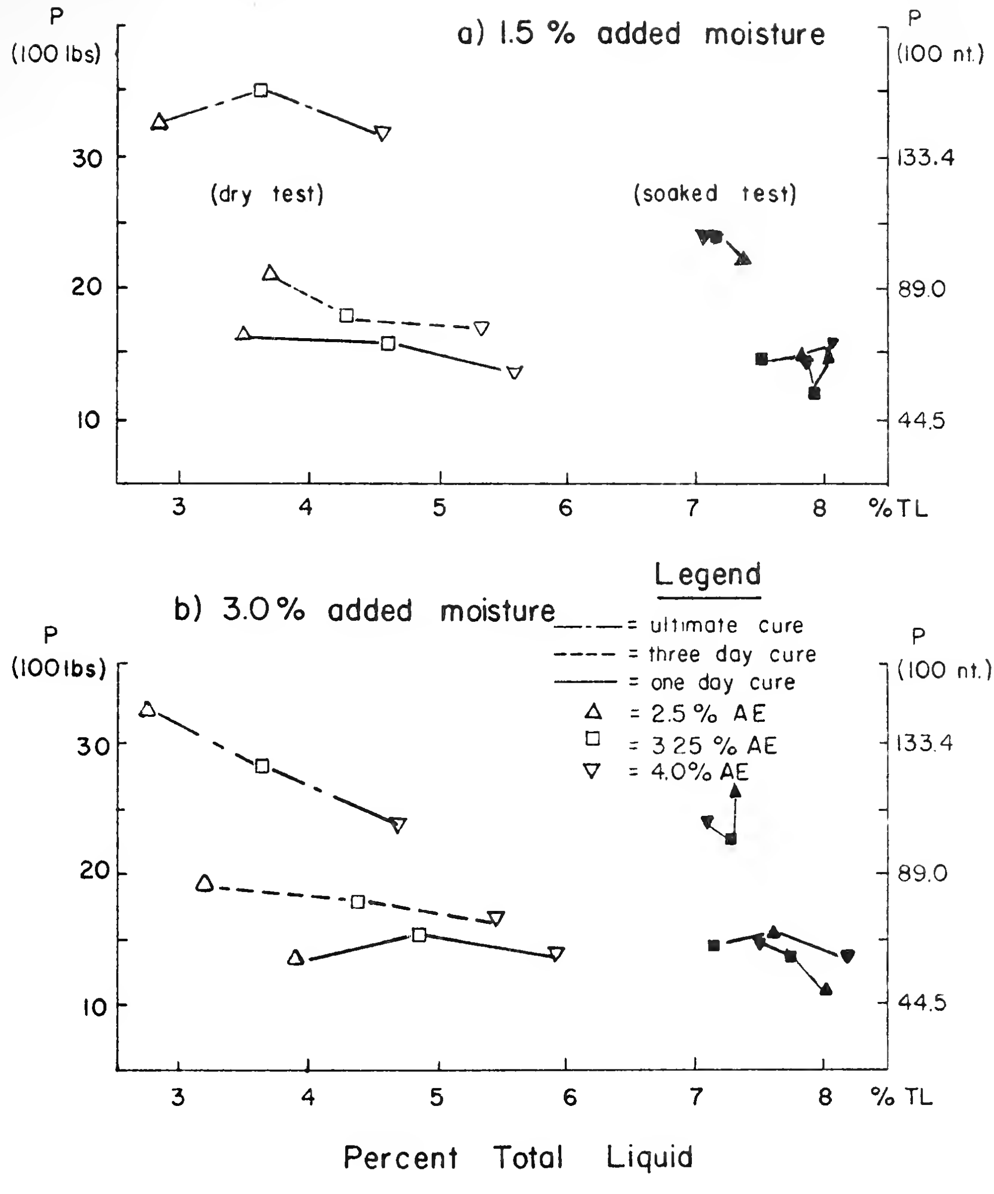

Figure 19. Marshall Stability for Dry and Soaked Specimens as a Function of Curing and Total Liquid (Mid-point Gradation)

curing condition. This would indicate that the reduction of sample moisture to less than one percent is crucial for high strength mixes; regardless of the test type.

The role of the second most important factor, AE residue, content is not so apparent. As shown by the ANOVA analysis it has no significant effect on the samples tested saturated. The samples tested dry show a decrease in stability with increasing AE residue content for all but two cases: the one day cure with 3% added moisture and the ultimate cure with 1.5% added moisture. However this trend is only generally significant for the ultimate curing condition. The two exceptions mentioned above show a small but significant peak at the mid AE residue content.

Although these results are not what one would expect from the standard Marshall test, they do correspond to the results obtained by Dr. Gadallah (18). It seems that the increased moisture from higher emulsion levels becomes trapped in the process of providing better coating and inhibits the full effect of the binder. The failure of the mix to densify with increased asphalt, as exhibited by the constant VMA, may also have some effect.

The influence of added moisture is still very slight. Generally the samples with 3% added moisture had stability values only slightly less than those with 1.5% added moisture. However, this is only significant for the upper asphalt levels of the ultimate curing condition tested dry. The effect of this variable on total liquid has already been described. In Figure 19 the effect of added moisture effect on total liquid at the time of test is also shown to be negligible. In the soaking test the samples with lower asphalt contents absorb more moisture so that the total liquid is approximately the same for all the samples.
The figure shows that, within the range tested, the increase in total liquid has less effect on the early curing conditions than for the ultimate cure. This is shown by the percent retained stability and the slope of the samples tested dry.

Looking specifically at the retained stabilities shown in Figure 18, the general trend seems to show little change between 2.5% AE residue and 3.25% resudue levels, but a much larger change at 4.0% AE residue. This change is an increase for all but the early cures with 1.5% added moisture. Thus the retained stability approximates the expected results for a mix with a Marshall optimum apshalt content between five and six percent.

Marshall Flow

Flow values are usually not as consistent or well behaved as the stability values. However in this study the expected trends are fairly well defined. In spite of the stability results, ANOVA analysis for this variable shows that for either type of test the only significant variables are curing and asphalt content. This is to be expected s since curing increases stability and the asphalt content affects the plasticity of the mix.

The graphical presentation of the results are shown in Figure 20. The dry tests show an excellent correlation with the ANOVA results. All the curing conditions show an increase in flow with increased AE residue contents and in all but two cases the flow increased with curing. However it should be noted that the variation in flow caused many of these trends to be statistically insignificant. The cure was only significant for the samples with 3% added moisture and 2.5% AE residue. The increase due to AE residue was not significant for the ultimate curing condition. Generally, the samples with 1.5% added moisture have slightly higher flow values but this effect is decreased, and even reversed, with longer curing. In none of the tests is there a significant difference between the two added moisture levels.

The soaked test results don't seem to follow any particular pattern and are much more variable than in the dry

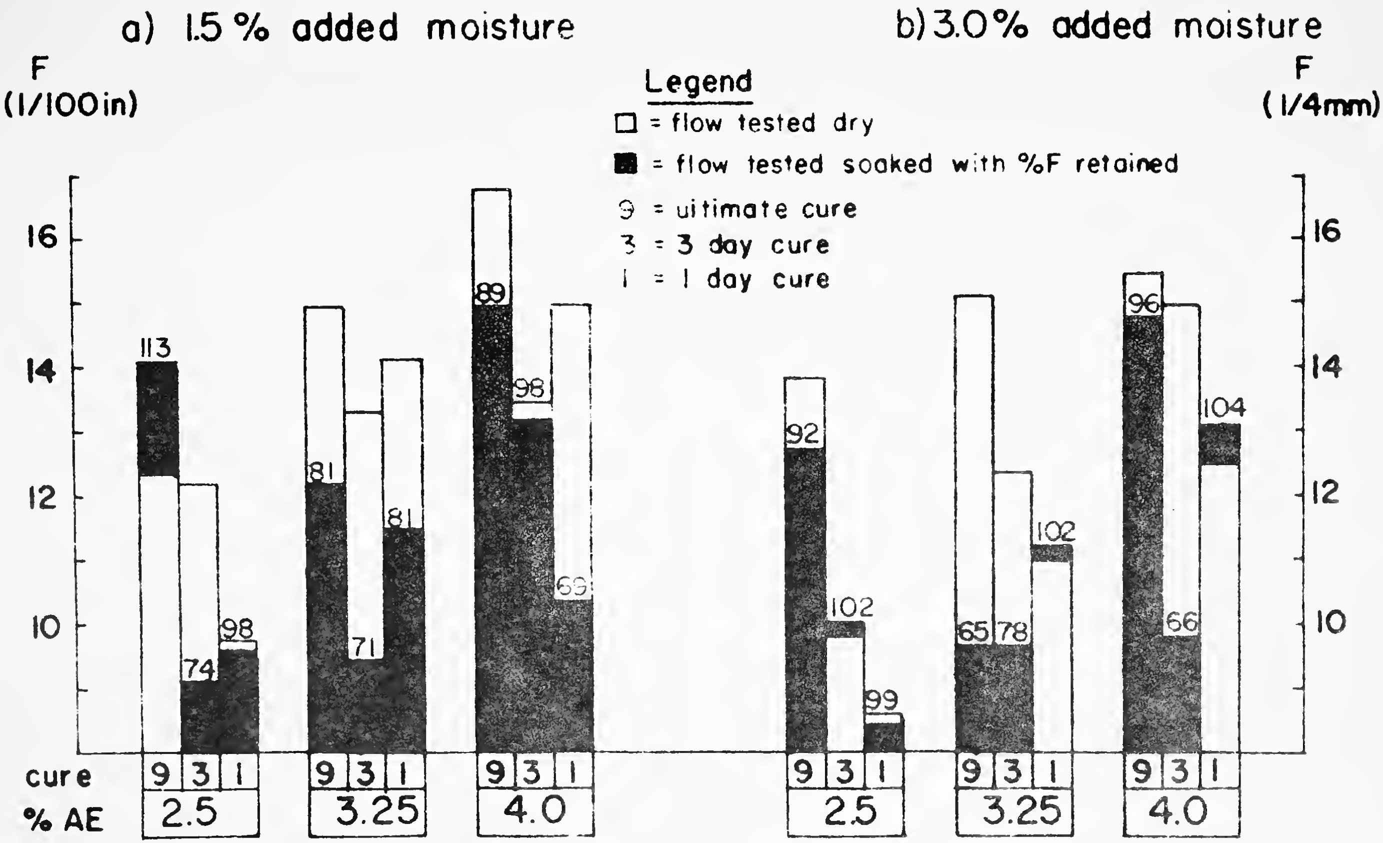

Figure 20. Marshall Flow for Dry and Soaked Specimens as a Function of Curing and AE Residue Content (Midpoint Gradation)

test. The samples with 1.5% added moisture again have flow values slightly higher than those with 3%. With increased AE residue contents there is a random increase in flow among the curing levels. Because of their high stability the ultimate curing condition has the highest flow. Since the one and three day cures had essentially identical stabilities, it would be expected that the more plastic samples with only one day cure would have the higher flow. Because of the large variation present, none of the values were statistically different.

Marshall Stiffness

The Marshall stiffness is an aggregated variable formed by dividing the Marshall stability by the Marshall flow. It may be expected that the greater variability in flow values would determine the trends for this variable. The ANOVA analysis would also indicate this. For both tests the curing and asphalt factors are significant while the dry test also shows the interaction of curing and added moisture to be significant.

However, when the results are plotted (see Figure 21) the strong pattern exhibited by the stability values is also apparent. Both types of test show a slight increase in stiffness from one to three days cure but then a much larger increase for the ultimate curing condition. For all but one case there is some decrease in stiffness with increased AE residue content. The exception (ultimate cure, 1.5% added moisture, soaked test) is easily explained by an unusually high value at the lowest AE residue content. This trend is not generally significant, especially for the samples tested vacuum saturated. Although the effect of added moisture is nearly the same as the AE residue content, the ANOVA analysis shows that this variable is not significant. Of the samples tested dry the ultimate curing condition shows higher values for samples with 1.5% added moisture while

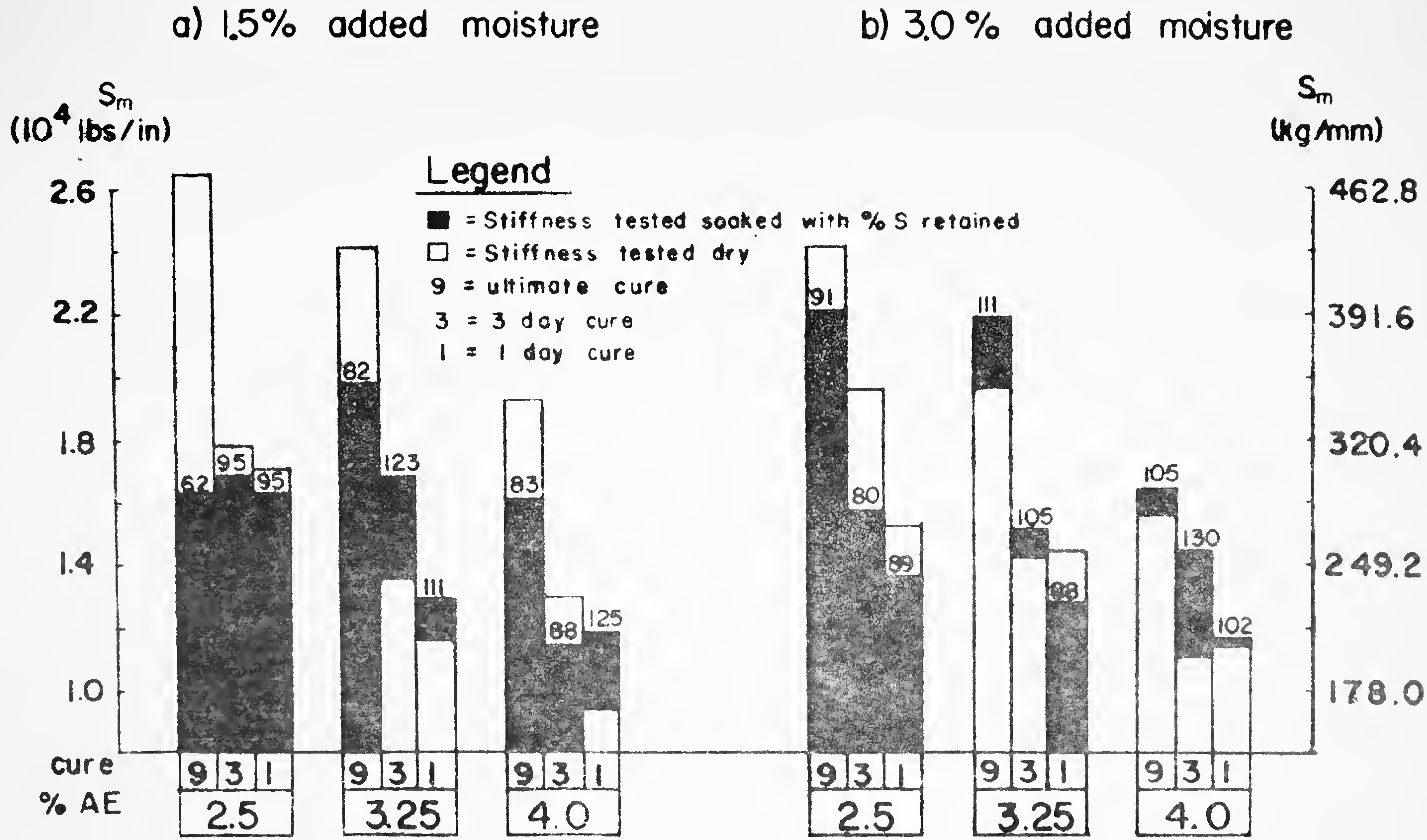

Figure 21. Marshall Stiffness for Dry and Soaked Specimens as a Function of Curing and AE Residue Content (Midpoint Gradation)

the early curing conditions showed the opposite. In the case of the saturated test, this pattern was simply reversed.

Marshall Index

The Marshall Index is the slope of the linear portion of the stability-flow deformation curve. Thus it forms a modulus of deformation for the mix being tested. By definition it will always be greater than the stiffness variable. In this study it was as much as three times the stiffness value. In the dry test the ANOVA analysis shows all of the factors to be significant for the transformed index. The factors significant in affecting the stability are also significant for the index, plus the interaction of AE residue and added moisture. However, in the soaked test the effect of AE residue and cure are the only significant factors affecting the Marshall index; indentical to the results for the flow and stiffness variables.

The plot of the index values in Figure 22 show an unexpected trend for the dry tests. Only those samples with 3.25 or 4.0 percent AE residue and 1.5 percent added moisture show a continued increase in index with longer curing. As a result, the AE residue variable is only significant for these two cases. The other cases all show an insignificant peak at three days cure. Although the three day cure only shows about 60% of its ultimate strength, it has an index 1.5 to 2 times that shown by the ultimate curing condition. In general the samples with 1.5% added moisture show values slightly greater than those with 3%. As for the stability values, this is only significant for the upper asphalt levels of the ulitmate curing condition.

The water sensitivity test results follow the expected pattern. There is an increased index value with longer curing and a decrease with higher asphalt contents. This is the same pattern displayed by the Marshall stiffness values. The effect of added moisture, though not significant,

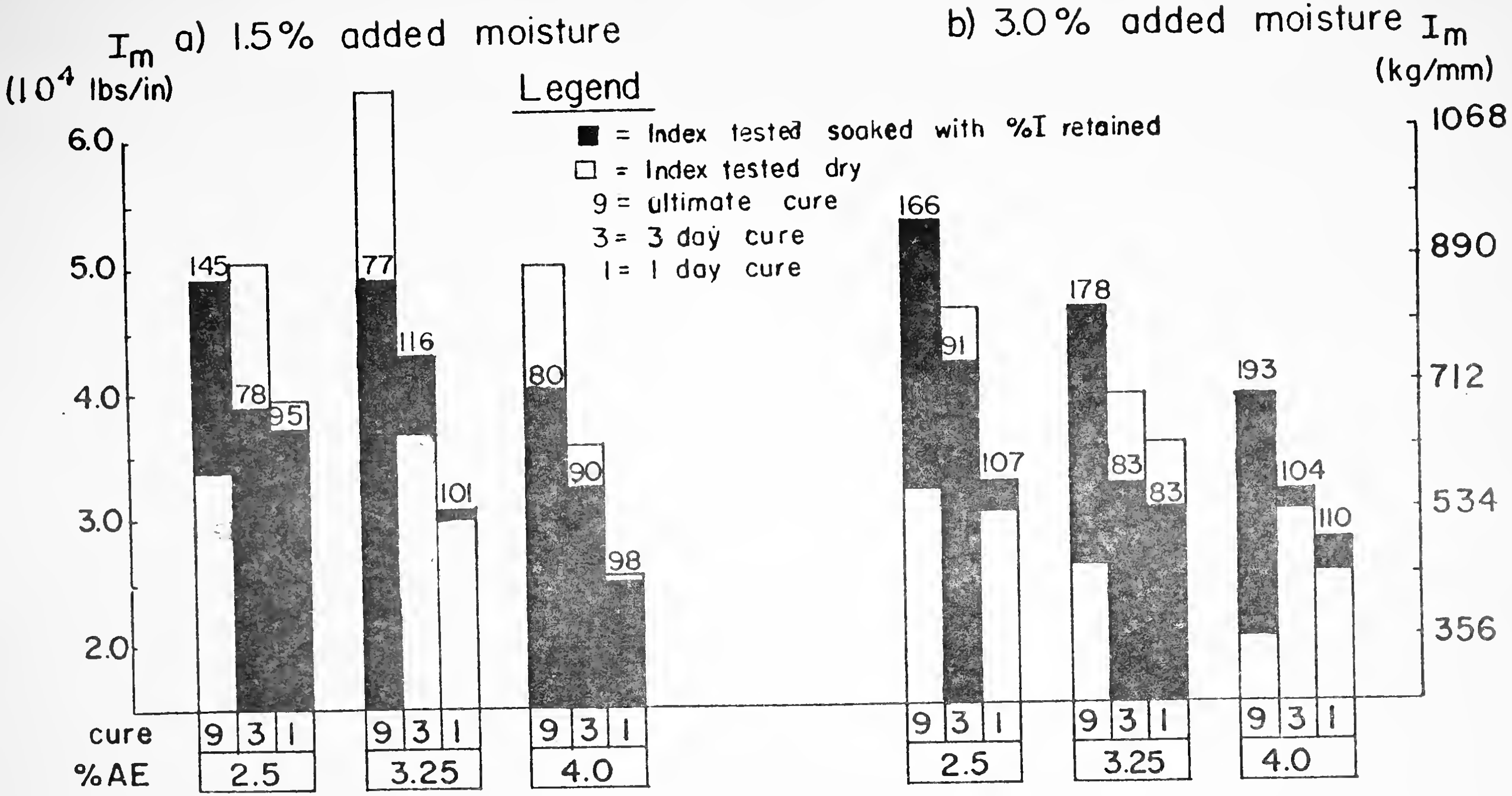

Figure 22. Marshall Index for Dry and Soaked Specimens as a Function of Curing and AE Residue Content (Midpoint Gradation)

was also the same as for the stiffness variable. At the ultimate curing condition the samples with 3% added moisture showed a higher index while just the opposite occurred for the early curing conditions.

Summary

In this chapter the influence of three factors on AETM behavior was investigated. Three levels of asphalt content, three levels of curing and two levels of moisture added to the dry aggregate were used in the analysis. The response variables measured include density and void variables as well as the Marshall test parameters. The mixes were tested in two conditions: air cured and vacuum saturated.

The results of the ANOVA analysis are shown in Tables 5 and 6. It can be seen that the water sensitivity test eliminates nearly all of the interaction terms leaving the main effects of the factors investigated. The significance of these factors is quite different for the two types of test; even for the sample properties which were measured before the sample saturation. The results of the soaked test generally give a much better indication of the actual significance of the factors investigated.

The effects of the three factors will now be summarized. The added moisture, with only two levels of 1.5% and 3.0% was not generally significant for any of the response variables. However the mixes with 3.0% added moisture usually had slightly lower values for the Marshall parameters due to the higher retained moisture levels. The effect of curing time is generally significant for all of the variables except the voids in the mineral aggregate and Marshall index. The AE residue content had a significant effect on the Marshall flow and all of the sample properties except the VMA. The most important factor for the sample characteristics seems to be the AE residue content while the curing time becomes more important for the Marshall variables.

CHAPTER 5: EFFECT OF AGGREGATE GRADATION ON AETM PROPERTIES

Introduction

In this chapter the main emphasis is placed on describing the effect of aggregate gradation; although the added moisture, AE residue content and curing factors will also be discussed. Three gradations were selected to represent the ISHC #73-B gradation specification. These gradations are identified as FG, MG and CG. They follow the upper limit, the midpoint and the quarter point of the specification band. A more detailed description may be found in Chapter 2.

Only the early curing conditions were used in this analysis. The cells tested and the variable levels are shown in Figure 23. Besides the three gradations there are two levels of cure, two levels of added moisture and three levels of asphalt emulsion residue. Emphasis is placed on the early curing conditions because they showed trends similar to the ultimate cure and also because early curing represents the most critical period of the mix performance.

Analysis of Results

A statistical analysis of this section is complicated by the presence of empty cells. This required the use of two different ANOVA's to analyze sections of the experiment. First, the samples cured for three days were analyzed using both ANOVA and the Student-Newman-Keuls multiple comparison procedures. The SNK test was also used to evaluate the vacuum saturation test results.

Curing Time		ONE DAY		THREE DAY	
% W Added Moisture		1.5	3.0	1.5	3.0
Gradation	% AE (residue)				
FG	2.5	△	△	⊗	△
	3.25	○△	○△	⊗	○△
	4.0			⊗	△
MG	2.5	⊗	⊗	⊗	⊗
	3.25	⊗	⊗	⊗	⊗
	4.0	⊗	⊗	⊗	⊗
CG	2.5			⊗	△
	3.25	○△	○△	⊗	○△
	4.0			⊗	△

Legend:

X = 3 samples tested 'dry'
O = 2 samples tested 'soaked'.
△ = 2 samples tested 'dry'.

Figure 23. Experimental Design to Investigate the Effect of Aggregate Gradation

The samples with 3.25% AE residue were also analyzed by an ANOVA analysis for all gradation levels and both of the test types. The results of these analyses are shown in Tables 7 and 8. To meet the requirements for the ANOVA analyses the original data was checked for homogeneity of variance by the Foster-Burr Q test and for normality by the use of normal probability plots. The results of the Q test are shown in Table 9. For the dry test only the Marshall index was shown to be nonhomogeneous so the logarithmic transformation was again applied to this variable. All of the variables possess homogeneity for the water sensitivity test.

The Student-Newman-Keuls procedure was used to check the number of cases included in a significant ANOVA result. A pairwise comparison of all the group means was conducted to assemble homogeneous subsets in which no pair differs by more than the shortest significant range for a subset of that size. The actual test is as follows:

$$|\overline{X_i} - \overline{X_j}| < R(\alpha,p,f)S_{\overline{x}} \quad (0.5^* \text{ within groups mean squares}^* \; \frac{N_i+N_j}{N_iN_j})$$

where R is a tabular range value dependent on the alpha level (0.05 is used here), the subset size (p), and the degrees of freedom (f) in the between groups sum of squares.

The ANOVA analysis of the samples cured for three days is based on the following model:

$$Y_{ijk\ell} = \mu + A_i + G_j + W_k + AG_{ij} + AW_{ik} + GW_{jk} + AGW_{ijk} + \varepsilon_{(ijk)\ell}$$

Table 7: Summary of ANOVA Results for the Dry Test (Phase I, 3 day cure)

Response Variables	Source of Variation						
	G	A	W	GA	GW	AW	GAW
γ_D			NOT SIGNIFICANT				
γ_W							
WC_o	S-	S-	S-	S-	S-	S-	
V_W	S-	S-	S-	S-	S-	S-	
V_A	S-	S-	S-	NS	S-		
V_T	S-	S-	S-	NS	S-		
VMA	S	NS	S-	NS	NS		
P	S-	S-	S-	S-	S-		
F	NS	S	NS				
S_m	NS	S-	NS		NOT SIGNIFICANT		
I_m	NS	S	NS				S
log (I_m)							

Symbol	α Level
S-	$0 < \alpha \leq .009$
S	$.009 < \alpha \leq .05$
NS	not significant

Table 8: Summary of ANOVA Results
(Phase I, early cures, mid AE residue content)

Dry Test					Response Variable	Soaked Test						
Source of Variation						Source of Variation						
G	C	W	GC	GW		G	C	W	GC	GW	CW	GCW
NOT SIGNIFICANT					Y_D	NOT SIGNIFICANT						
					Y_W	S-	NS	S	S		S-	S
S-	S-	S-		S	WC_o	NS	S-	S-	NS		S-	NS
S-	S-	S-			V_W	NS	S-	S-	NS		S-	NS
S-	NS	NS			V_A	S-	S	NS	S+		S-	NS
S	NS	S			V_T	S-	S	S-	S	S+	S-	S
					VMA	S-	S	S-	S	S+	S-	S
S-	S	S-	S	S-	P	S	S-	S-	S-			
S-	S	S	NS	NS	F	S	NS	NS	S			
S-	NS	NS	NS	NS	S_m	S-	S-	NOT SIGNIFICANT				
NS	NS	NS	NSN	NS	I_m	NS	S-					
NS	NS	NS	NS	NS	$\log I_m$							

Symbol	α Level
S-	$0 < \alpha \leq .009$
S	$.009 < \alpha \leq .05$
S+	$\alpha \leq .1$
NS	Not Significant

Table 9: Results of Phase I Homogeneity Test*
(All mixes tested)

Response Variables	Dry Test 36 samples, 2 d.o.f.** 1). $Q_{2,36,0.001} = 0.100$ 2). $Q_{2,36,0.001} = 0.082$		Soaked Test 24 samples, 1 d.o.f. 3). $Q_{1,24,0.001} = 0.302$ 4). $Q_{1,24,0.01} = 0.224$	
	Q statistic	Homogeneity	Q statistic	Homogeneity
G_D	0.071	accept Q_2	0.114	accept Q_4
G_W	0.078	accept Q_2	0.119	accept Q_4
WC_o	0.076	accept Q_2	0.137	accept Q_4
P	0.059	accept Q_2	0.139	accept Q_4
F	0.074	accept Q_2	0.215	accept Q_4
S_m	0.099	accept Q_1	0.188	accept Q_4
I_m	0.230	accept Q_1	0.103	accept Q_4
log (I_m)	0.092	accept Q_1		
V_W	0.072	accept Q_2	0.136	accept Q_4
V_A	0.078	accept Q_2	0.099	accept Q_4
V_T	0.072	accept Q_2	0.113	accept Q_4
VMA	0.071	accept Q_2	0.114	accept Q_4

* Foster Burr Q test for Homogeneity of Variances
** Degrees of Freedom

where

$Y_{ijk\ell}$ = measured or response variable

μ = overall true mean

A_i = true effect of AE residue content, %AE

G_j = true effect of gradation

W_k = true effect of added moisture content, %W

$\varepsilon_{(ijk)\ell}$ = true random error, NID $(0,\sigma^2)$

The subscripts i, j and ℓ may take on the values 1, 2 or 3 while K may be 1 or 2. In the analysis of the samples with the mid asphalt content the same model is used with the AE residue term being replaced by two levels of curing.

Sample Density

The first response variable to be investigated is the sample density. The analysis for the air cured and oven dry density was identical so only the "wet" density will be discussed. This density is plotted as a function of total liquid in Figure 24. The results for the specimens to be tested vacuum saturated were so closely matched with those to be tested dry that the average of all the cell replicates was plotted in the graphs.

A linear increase in density is observed for increases in total liquid. The gradation lines are parallel for the mixes with 3.0% added moisture but converge at the 4.0% AE residue for the mixes with 1.5% added moisture. The latter mixes also show different levels for the two curing periods. The one day cure patterns are identical to those for 3.0% added moisture while the fine and coarse gradations of the three day cure are much higher. It is only for these mixes that the effect of added moisture and cure are significant. The one day cures have a definitely

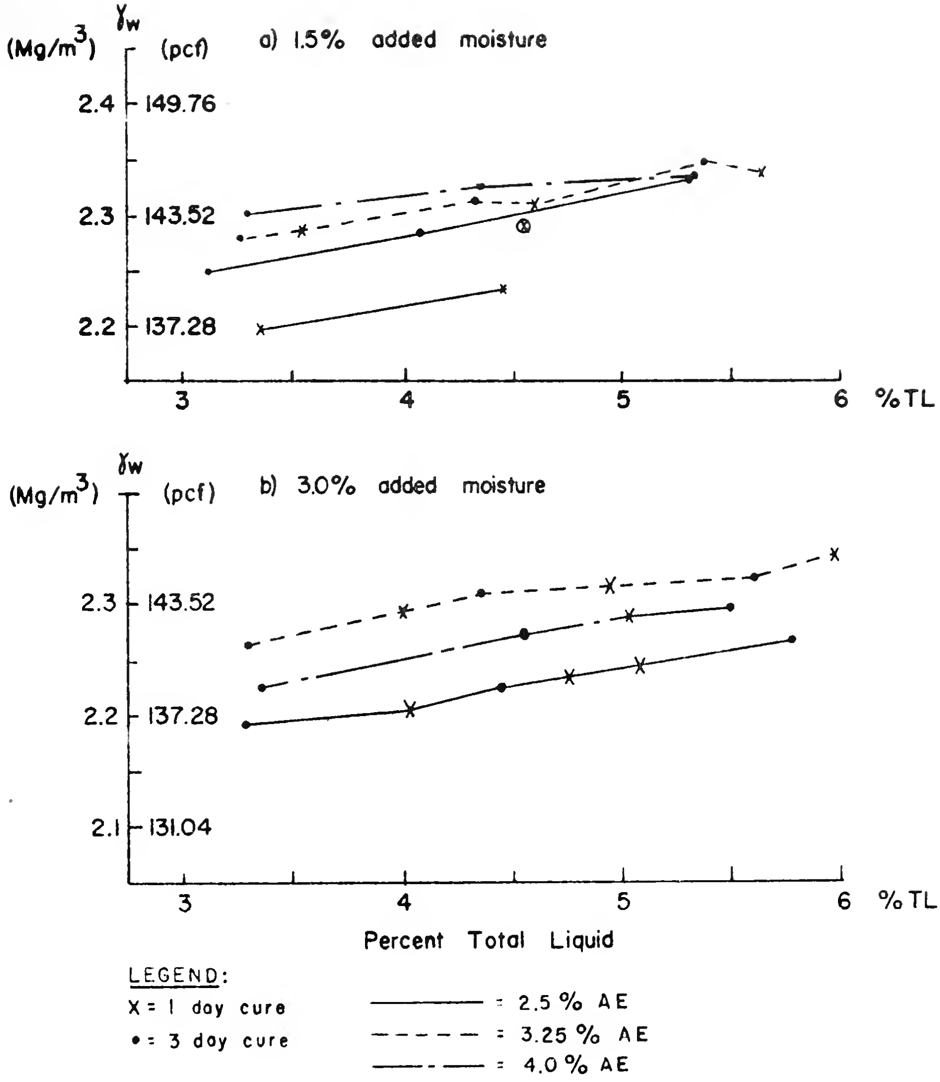

Figure 24. Average Sample Density for All Specimens as a Function of Gradation Cure and Total Liquid

higher liquid content, especially with 3.0% added moisture, but this only causes an insignificant increase in density. Figure 24 shows that both cures form a single pattern for each gradation.

The effect of AE residue content and gradation have a much greater effect on density. Gradation is generally significant for the mixes with 3.0% added moisture and follows the expected pattern where the midpoint achieves the highest density and the fine gradation the lowest. For mixes with 1.5% added moisture and three days cure the effect of gradation is only significant at the 2.5% AE residue level. This is due to the converging trend already mentioned. The AE residue content forms the largest part of the liquid content and has the greatest impact of all the factors. the SNK analysis shows that the AE residue factor is significant for all of the mixes.

Air Voids

The air voids follow the patterns shown by the sample densities. At higher densities a decrease in voids would be expected. As can be seen in Figure 25, this is exactly what has happened. The midpoint gradation had the highest density and thus has the lowest air voids. This forms the "V" pattern shown in the figure. It may be noted that the coarse gradation represents the quarter point in the gradation band and thus shows only half of the change between the fine and midpoint gradations. The mixes with three days cure with 1.5% added moisture also follow their density pattern with the coarse gradation having even fewer voids than the midpoint.

The samples again showed good replication for the two test types. The grand mean was plotted when the difference was less than 1% V_A (approximately four standard deviations) and the dry test value was used in establishing the trend

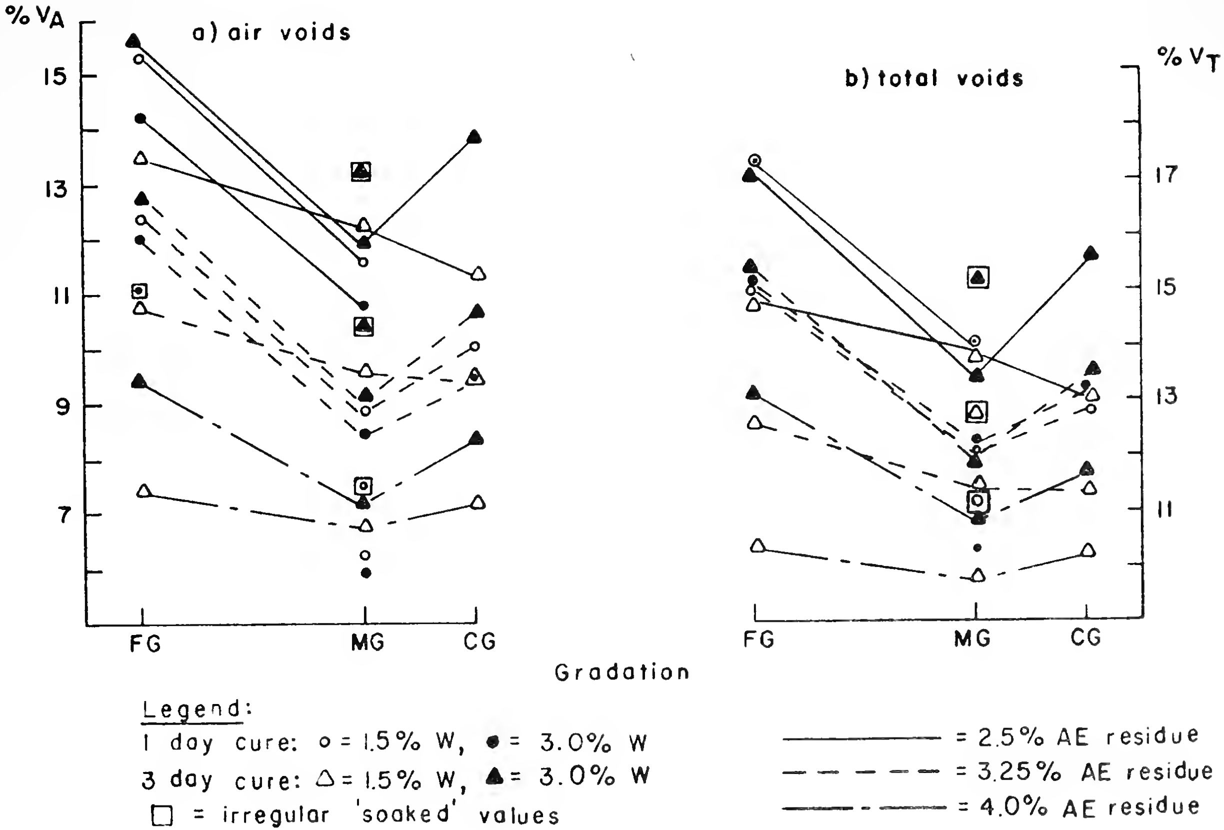

Figure 25. Air and Total Voids for All Specimens as a Function of Cure, Gradation, Added Moisture and Residue Content

for differences greater than this range. The three values outside this range all show higher void contents for the samples to be tested saturated. This would only result in a shallower "V" pattern without changing the factor interactions.

The effect of the factors on this variable are exactly the same as for the density. The higher moisture in the samples cured one day causes them to have slightly lower air voids. The higher moisture retained when 3.0% added moisture is used also causes these mixes to have fewer voids. However, because of the conflicting trends shown by the fine and coarse gradations with three days cure this pattern is reversed. The aberrant pattern for the three day cures with 1.5% added moisture causes the effect of gradation to be insignificant at the lower asphalt levels for the midpoint and coarse gradations and at the 4.0% AE residue level none of the gradations are significantly different. Otherwise the gradation and asphalt factors are both significant.

Total Voids

The same procedure used to plot the air voids was also applied in plotting the total voids. As would be expected by the nature of these voids, the cure and added moisture factors have negligible effects. Only the three day cures with 1.5% added moisture cause these factors to become significant at the fine and coarse gradations. As can be seen in Figure 25, these mixes have void levels progressively lower (even for the midpoint gradation) than the others with increases in AE residue content. The effect of AE residue is again the most important factor and is generally significant. The effect of gradation is again shown by the "V" pattern and is also generally significant. Only the three day cures with 1.5% added moisture are not significantly affected by the gradation factor.

Voids in the Mineral Aggregate

These voids are also affected by gradation and show trends very similar to the other voids discussed. The results for the samples with three days cure and 1.5% added moisture again show a continuous decrease in voids with coarser gradations instead of the expected "V" pattern. For these samples the gradation is not significant at the 3.25% AE residue level tested dry or at the 3.25% and 4.0% AE residue levels in the soaked samples. The general pattern, shown in Figure 26, is identical to that shown for the air and total voids.

None of the other factors have much influence on this variable. The AE residue content is not shown to be significant for any of the mixes tested. Because of the pattern exhibited by the mixes with 1.5% added moisture and three days cure, the effect of added moisture is shown to be significant for these mixes made with the fine or coarse gradations. This pattern also causes the effect of cure to become significant for these mixes made with the fine gradation.

Marshall Stability

The results of the dry test are presented in Figure 27. It can be seen that the three day curing results in a considerable gain in strength over the one day cures. The longer curing also results in a much greater effect of the control factors; in spite of the similarity of the sample properties.

The effect of gradation is not generally significant, even for the three day cures. Only the two upper AE residue levels for samples with 1.5% added moisture and three days cure showed a significant difference. These mixes showed a linear decrease in stability with coarser gradations; the

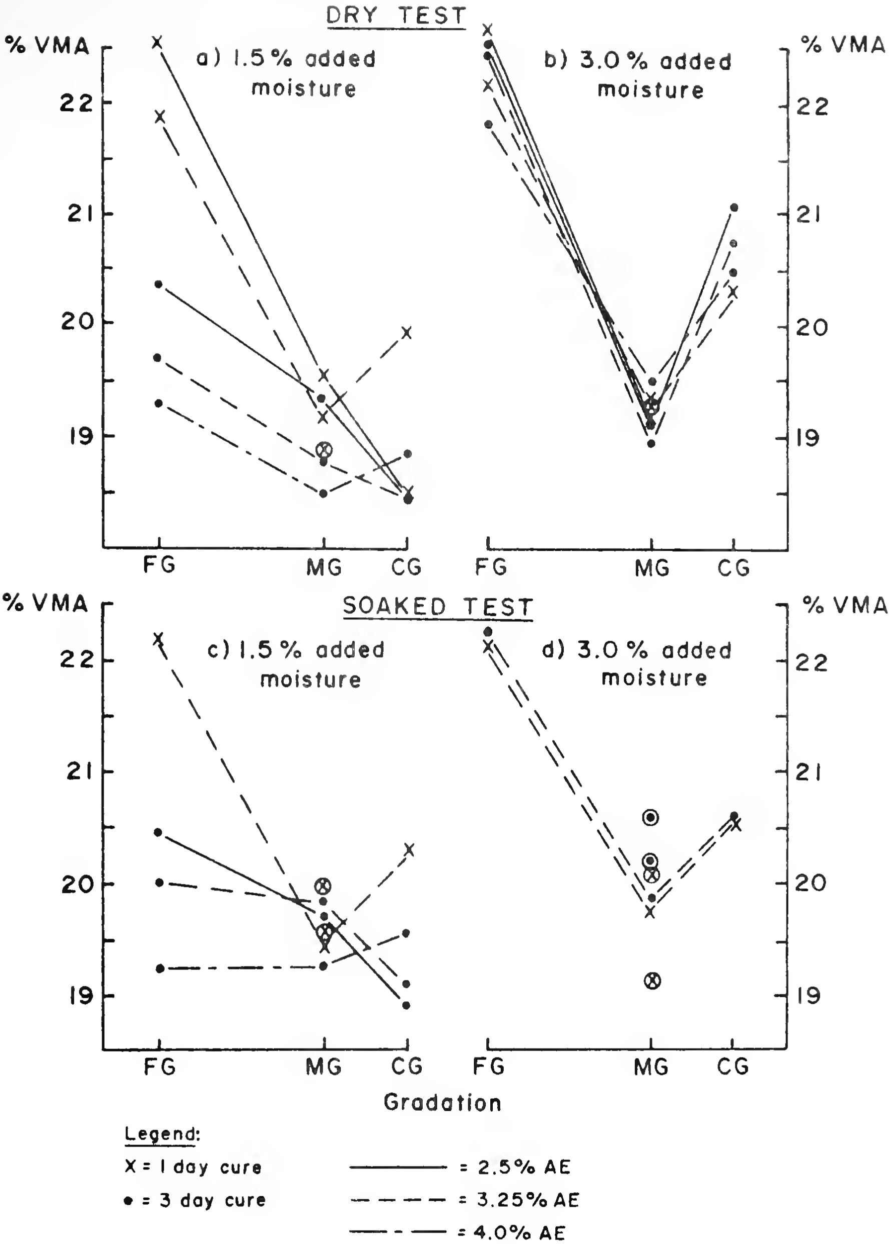

Figure 26. Percent VMA as a Function of Gradation, Cure, Added Moisture, Residue Content and Test Type

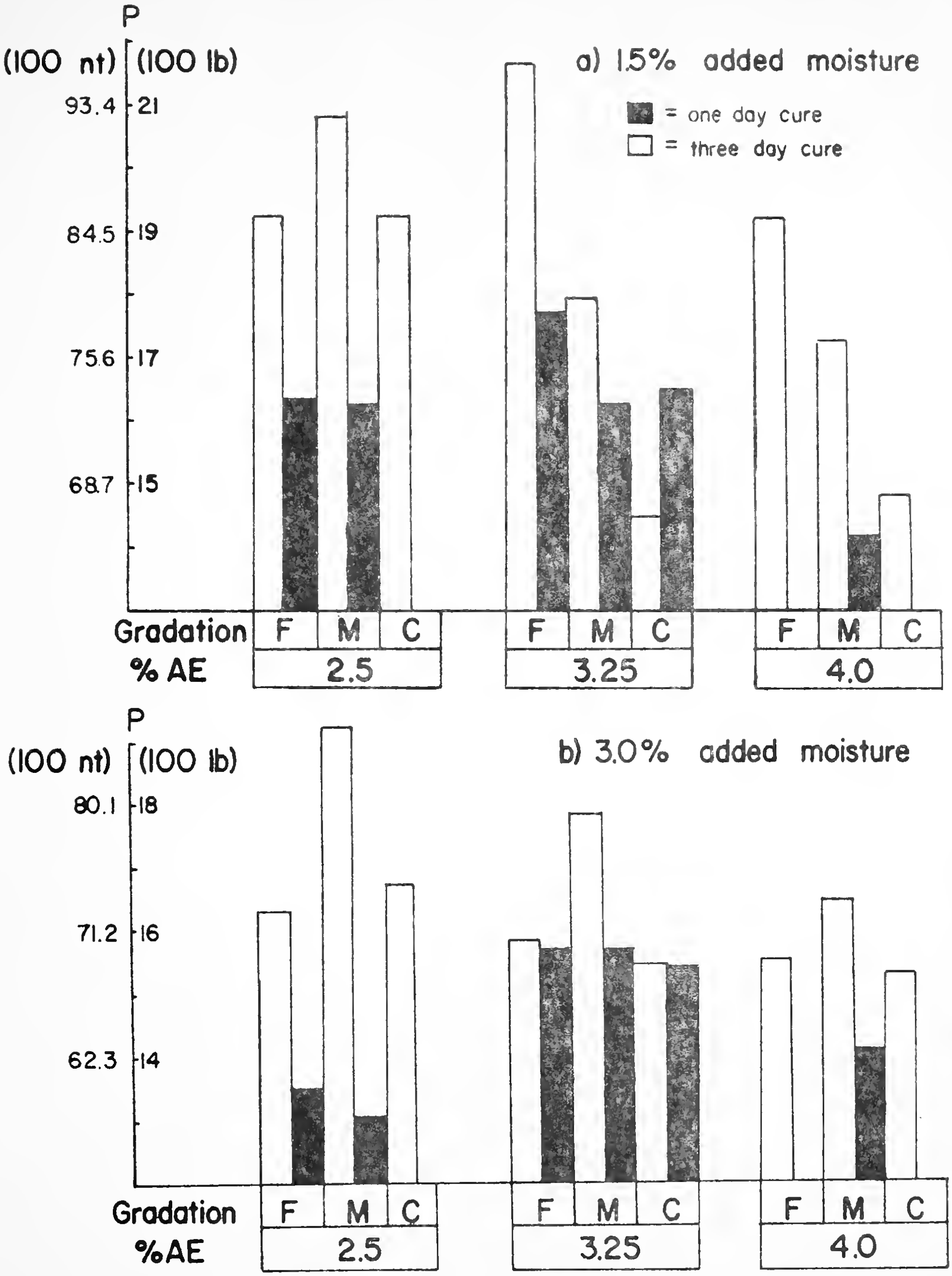

Figure 27. Marshall Stability Tested Dry as a Function of Gradation, Added Moisture and Residue Content

opposite of what would be expected from the density results. The other three day cures all show a peak stability at the midpoint gradation while the one day cures show no effect from this factor.

The effect of asphalt content or added moisture is not generally significant for either of the curing conditions. The increase in asphalt content causes a slight decrease in stability for mixes with three days cure. However this is only significant for the coarse and midpoint gradations with 1.5% added moisture. The fine gradation with 1.5% added moisture and all of the one day cures obtain a small, peak stability at the mid AE residue level. The effect of added moisture is significant for only three cases although the 3.0% moisture level usually has a slightly lower stability than does the 1.5% level.

The results of the vacuum saturation test are plotted in Figure 28. The SNK analysis shows that only the cure for the fine gradation is significant. As shown in the previous chapter, the AE residue factor has little effect for this test at the early curing conditions. The samples with 3.0% added moisture show a stability 100 lbs to 200 lbs (444.8-889.6 nts) less than the samples with 1.5% added moisture. The one day cure shows a peak at the midpoint gradation while all of the three day cures show a decrease in stability with coarser gradations.

Marshall Flow

The flow values used in this section again show very consistent trends. The one day cures have much higher relative flow values (with respect to the three day cure) than were their stability values. In two cases the one day flow is even greater than the three day value. Thus the cure only becomes significant for the samples with 1.5% added moisture and low AE residue content. (See Figure 29).

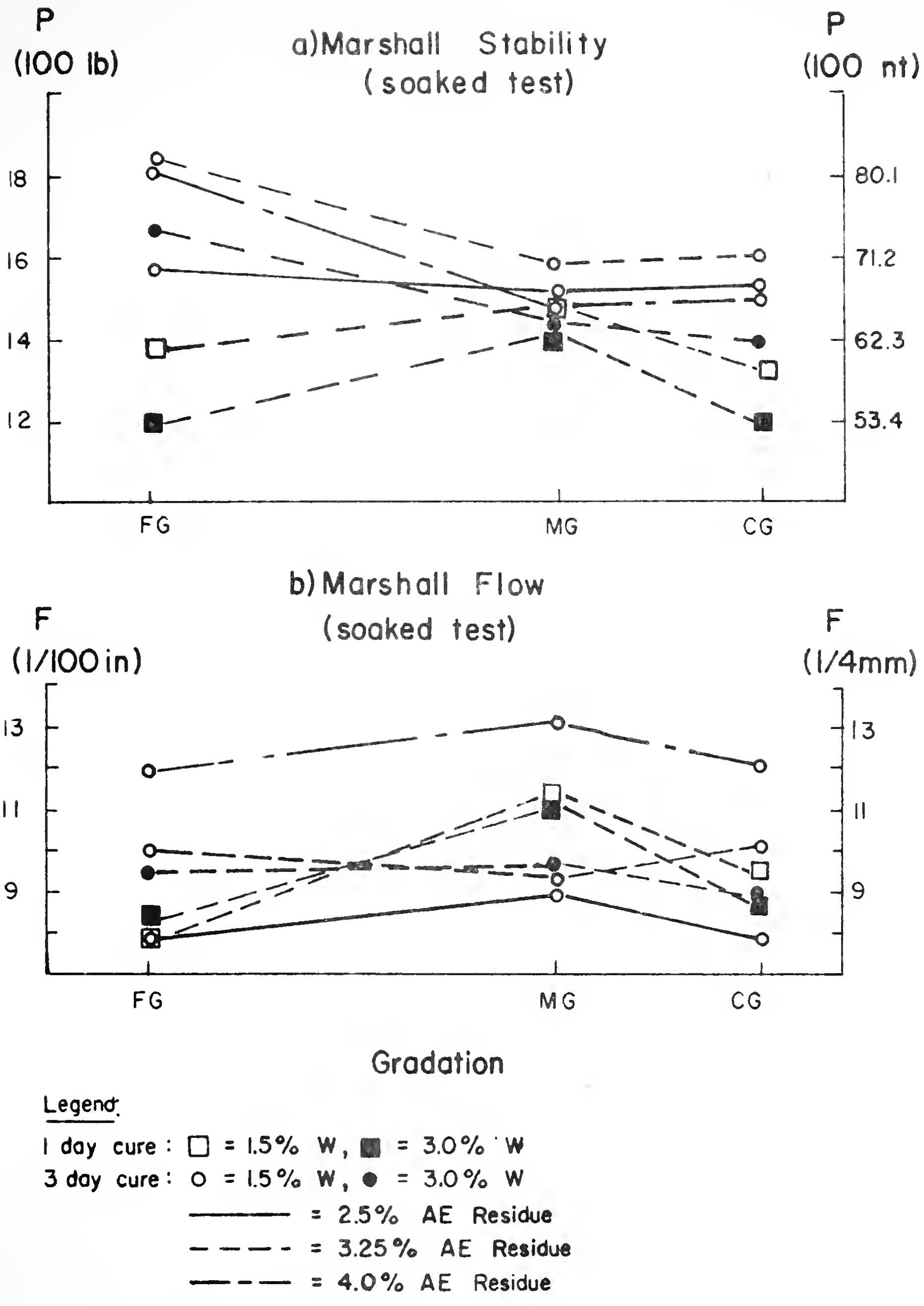

Figure 28. Marshall Stability and Flow Tested Vacuum Saturated as a Function of Cure, Added Moisture and Residue Content

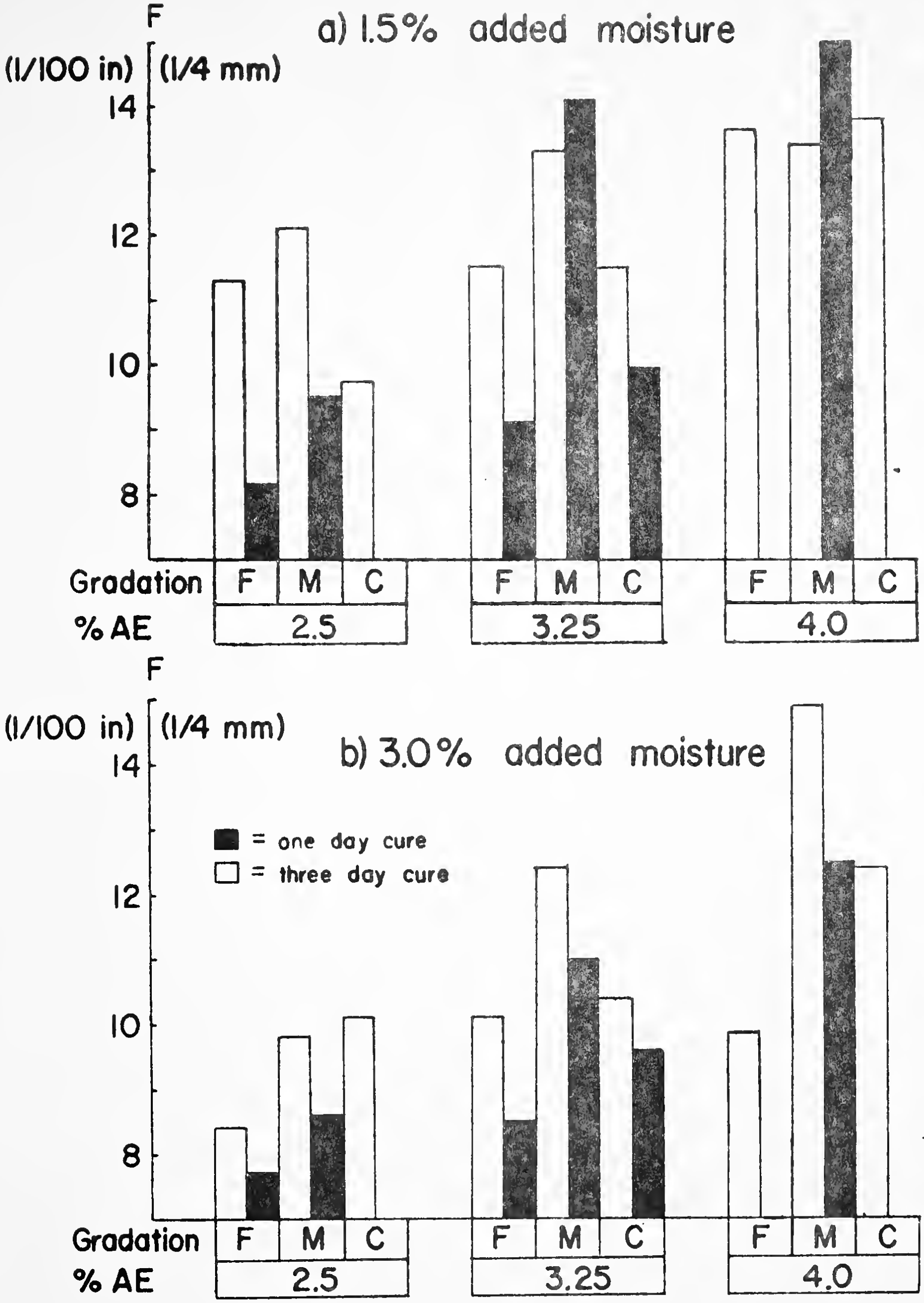

Figure 29. Marshall Flow Tested Dry as a Function of Gradation, Added Moisture and Residue Content

The effect of gradation is similar to that shown for the stability values at three days cure. Both curing levels show a peak flow at the midpoint gradation. This trend is accentuated with the increase in AE residue content. The SNK analysis only shows two cases to be significant: the three day cure with 3.0% added moisture and 4.0% AE residue and the one day cure with 1.5% added moisture and 3.25% AE residue.

The increased AE residue content results in an increased flow value for all of the mixes. The almost linear increase is shown to be significant by the SNK procedure for the three day cure with 3.0% W at the midpoint gradation and with 1.5% W at the coarse gradation and for the one day cure with 1.5% W at the midpoint gradation.

The level of added moisture is not significant for either of the two tests. The mixes with 3.0% added moisture have a slightly lower flow in the dry test but there is no difference in the soaked test.

The results of the soaked test are plotted in Figure 28. None of the factors have a significant effect and it can be seen that the patterns observed for the dry test results are also present here. Both curing levels show a very slight peak at the midpoint gradation. This would not be expected for the three day cures because of their decrease in stability with coarser gradation. The AE residue content again has the largest effect; causing higher flow for mixes with higher AE residue contents.

Marshall Stiffness

Since the stability and flow values showed similar trends it would be expected that the stiffness variable remains fairly constant. Figure 30 shows that this is the case. Neither the cure, added moisture or gradation is generally significant. Only the gradation showed

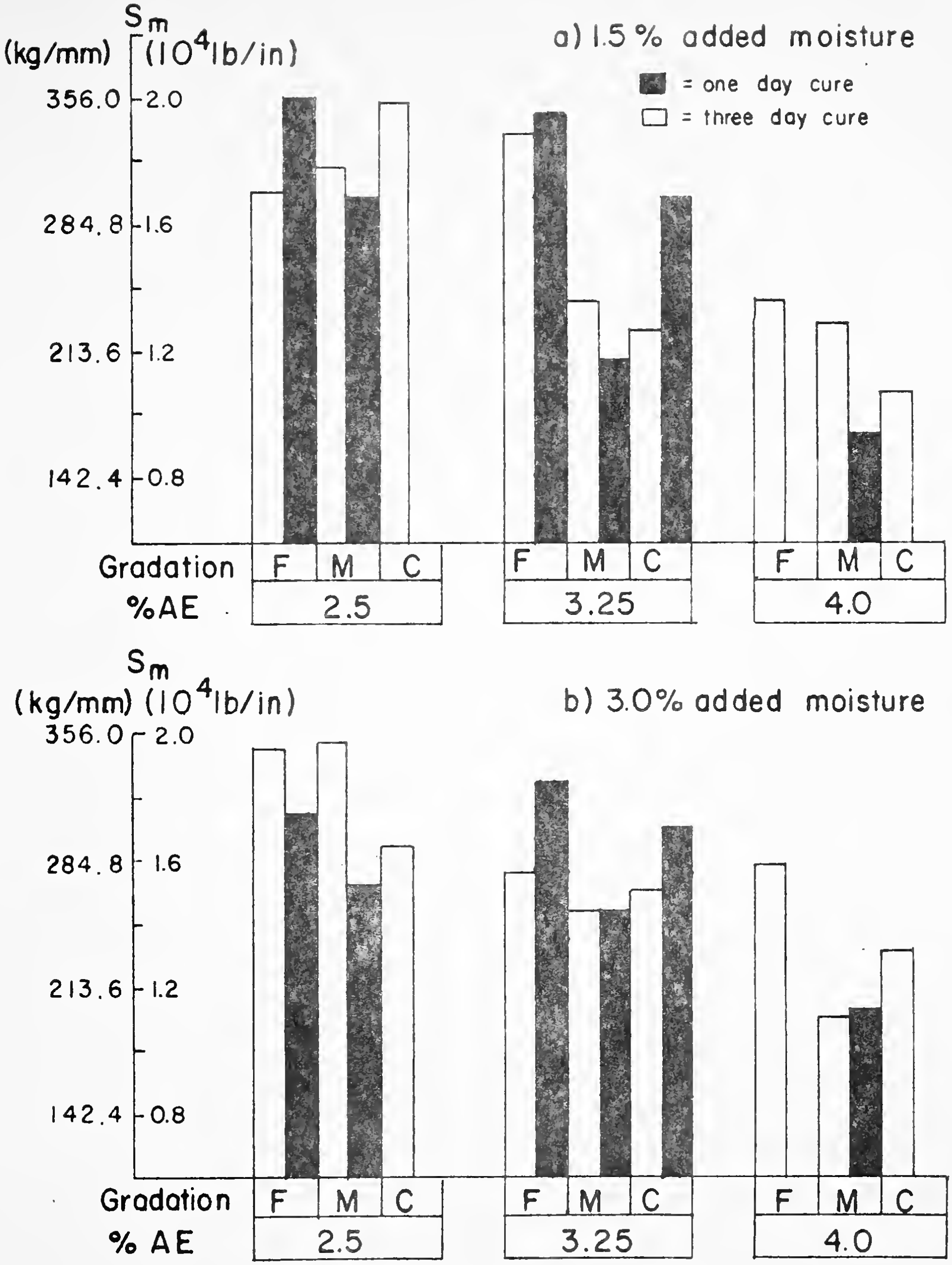

Figure 30. Marshall Stiffness Tested Dry as a Function of Gradation, Added Moisture and Residue Content

significance; for the mixes with 1.5% added moisture and 3.25% AE residue content. This may be attributed to the different trends for stability and flow at this AE residue level.

Most of the mixes show a near linear decrease in stiffness with increasing AE residue contents. This may be attributed to the significant increase in flow values, as well as a slight decrease in stabilities, with the increase in AE residue content. The fine gradation with one day cure and 3.0% added moisture or three days cure and 1.5% added moisture both show an asymmetric peak stiffness at the mid AE residue level. This trend is significant for all of the mixes with 1.5% added moisture and the midpoint gradation with 3.0% added moisture and three days cure.

The results of the water sensitivity test are shown in Figure 31. The effect of the factors is greatly reduced for this type of test. The SNK analysis shows that none of the factors are significant. There is a slight decrease in stiffness with increased AE residue content. The graph also shows a small "V" pattern effect for gradation. This pattern was very pronounced for the density and void variables. The one day cures are consistently less than the three day cure and the mixes with 3.0% added moisture are just a little less than those with 1.5%.

Marshall Index

The index values for the samples tested dry are presented in Figure 32. The results are very similar to those of the stiffness variable. The cure, added moisture and gradation have a very limited effect on this variable. The mixes with 1.5% added moisture have a slightly higher index at the low asphalt contents. The one day cure values generally show a "V" pattern and are less than the three day values which generally show a peaking pattern as a result of gradation.

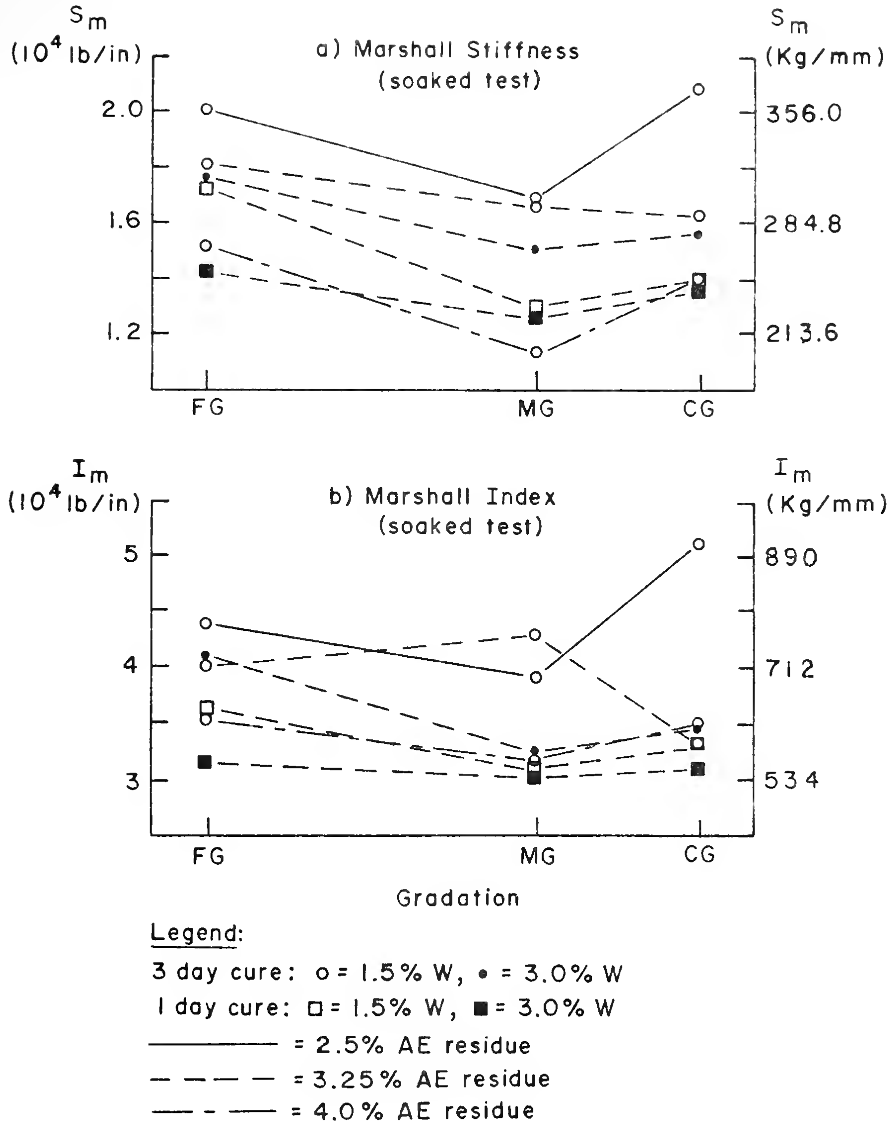

Figure 31. Marshall Stiffness and Index Tested Vacuum Saturated as a Function of Gradation, Added Moisture and Residue Content

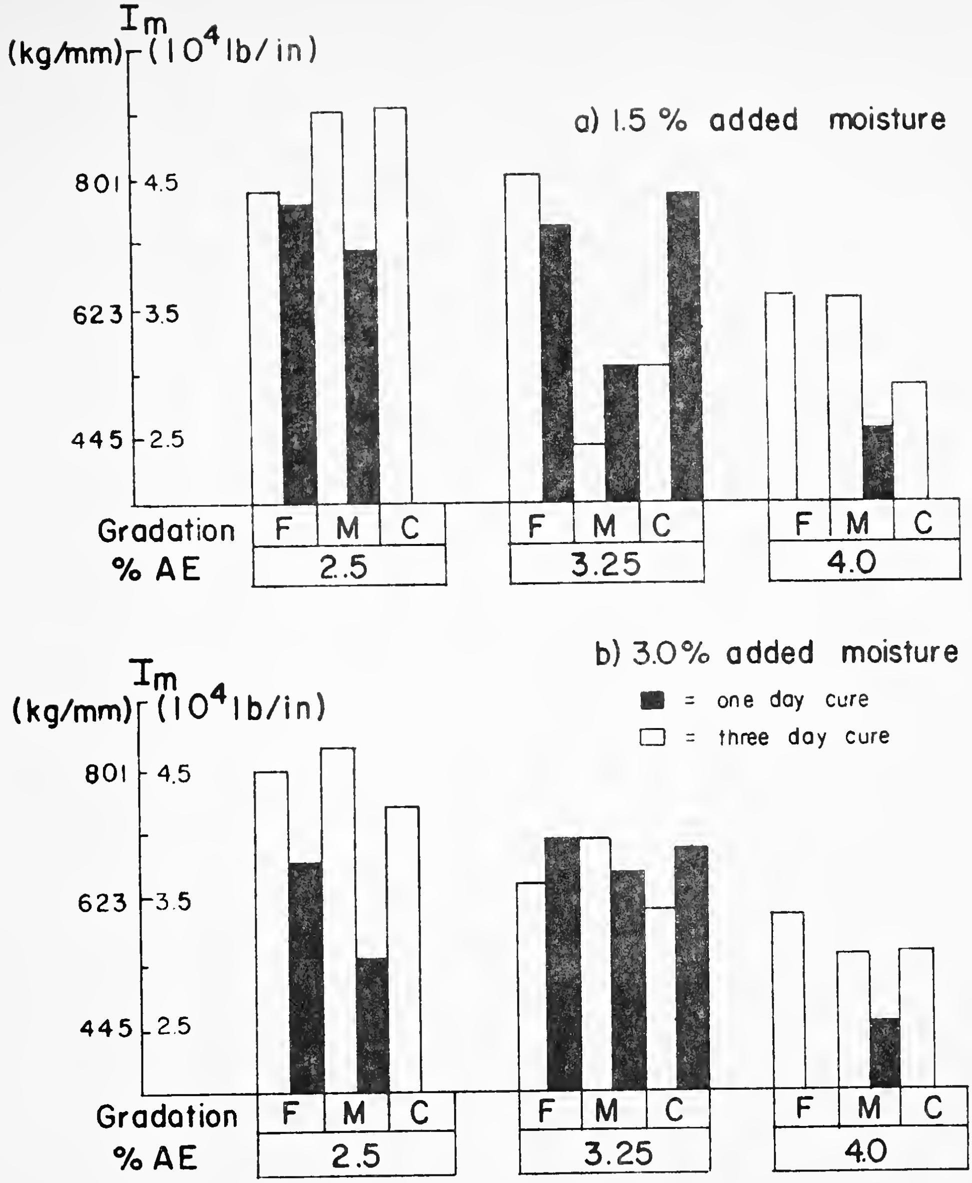

Figure 32. Marshall Index Tested Dry as a Function of Gradation, Added Moisture and Residue Content

The increase in AE residue content causes a general decrease in index for both curing levels. However the trend is not consistent enough to be significant. Only the three day cure, midpoint gradation samples showed a statistically significant decrease.

The results of the water sensitivity test show an even smaller impact of the factors. Only the effect of gradation for the three day cure with 2.5% AE residue is significant. The one day cures are slightly less than the three day cures and the mixtures with 3.0% added moisture are minimally less than those with 1.5%.

Summary

The samples showed very good replication of the sample density and void properties so all the values could be used to represent each mix combination. The results showed very strong and consistent patterns for these variables. Only the three day cures with 1.5% added moisture did not conform to the general pattern. If these mixes are ignored, the effects of the factors on the sample properties may be briefly summarized. The gradation was significant for all of the variables and had the largest effect. The asphalt emulsion residue content also had a large effect and was significant for all except the %VMA variable. The cure and added moisture factors were generally not significant.

The effect of the factors on the Marshall test parameters was very limited and was decreased even further in the vacuum saturated condition. None of the factors had a significant effect on the performance of the mixes when they were saturated. In the dry test only the amount of curing and AE residue had generally significant effects; for the Marshall stability and flow respectively.

CHAPTER 6: PHASE II: INFLUENCE OF BINDER TYPE

Introduction

This chapter deals with the influence of the type of bituminous binder added to aggregate. Specifically we wish to investigate any differences in behavior resulting from the use of asphalt cement instead of asphalt emulsion as the binder material. These two materials have very different characteristics, as well as different mixing procedures, so they may be expected to show differences in behavior when used in otherwise identical mixes. In addition the asphalt cement samples were tested for their water susceptibility in the water sensitivity test already described.

Experimental Design

This phase of the study is not nearly so extensive as the first and third sections. The graphical presentation of the experiment is shown in Figure 33. Since the gradations used in the first phase had a relatively insignificant effect only the midpoint gradation was used in this phase. In preparing the asphalt cement samples no initial moisture was added to the dry aggregate so this variable was also eliminated from this section. A curing period of one day for the asphalt emulsion samples was selected to facilitate handling, minimize slack time, perhaps be most representative of field practice, most nearly approximate the asphalt cement procedure, and also allow the incorporation of cells tested by Dr. Gadallah. Thus the only parameters tested are the amount of binder used and the aggregate type. The crushed limestone and the sand and gravel aggregates were

Gradation Midpoint	Aggregate Type	Binder Type / % Asphalt (residue): ASPHALT CEMENT 2.5	ASPHALT CEMENT 3.25	ASPHALT CEMENT 4.0	ASPHALT* EMULSION 2.5	ASPHALT* EMULSION 3.25	ASPHALT* EMULSION 4.0
	Limestone	X	X	X	⚹	⚹	⚹
	Sand & Gravel	X	X	X	O	O	O

Legend:

X = 3 samples tested 'dry' & 2 samples tested 'soaked'
⚹ = 3 samples tested 'dry'
O = 3 samples tested 'dry' by Dr. Gadallah

* samples with one day cure and no added moisture

Figure 33. Experimental Design to Investigate Binder Type

tested at the three binder contents used in phase I; 2.5, 3.25 and 4.0 percent by weight of the dry aggregate.

Experimental Procedures

In preparing the asphalt emulsion samples the procedure outlined on page 24 was used. This procedure was used throughout the study. The modifications required for this section are very minor. First, no moisture was added to the dry aggregate so this step was eliminated. Secondly, the samples were only allowed one day of air curing and then tested by the 'dry' test procedure described on page 26.

The samples using asphalt cement as the binder material were made according to the Standard Marshall hot-mix method. The aggregate, molds, asphalt, and mixing equipment were all heated to the mixing temperature of 300°F (149°C). After adding the asphalt to the aggregate the mixture was mechanically mixed for approximately one minute and then placed into the mold in two lifts. Each lift was rodded fifteen times to correspond with the procedure used with the procedure used with the emulsion binder. The mix was then compacted by receiving fifty blows of the mechanical hammer on each face. The samples were left to cool overnite before being extruded.

The asphalt cement samples were tested 'dry' by means of the following procedure. The height and specific gravity of the sample was measured as described for the asphalt emulsion samples. The samples were then placed in an oven at 140°F (60°C) for three hours. Just before the stability test the testing head was heated to approximately 100°F (42.9°C) to prevent temperature affects. At the time of test the sample was placed in the testing head and subjected to the standard Marshall stability procedure.

The asphalt cement samples subjected to the 'soaked' test followed quite a different procedure. Their heights

and specific gravities were measured in the same manner but they were then placed under a fan for half an hour. After this they were subjected to the soaking test as described on page 26. After one day of soaking they were placed in a water bath at 140°F (60°C) for half an hour. At the time of test they were carefully dried and placed in the warmed testing head for the Marshall stability test.

Analysis of Results

The data was analyzed using both ANOVA and Student-Newman-Keuls procedures to determine the significance and effect of the independent parameters. Two separate analyses were used to investigate first the effect of binder type, and then the effect of the soaking test on the asphalt cement samples.

To determine the effect of binder type the following model was used:

$$Y_{ijk\ell} = \mu + B_i + M_j + A_k + BM_{ij} + BA_{ik} + MA_{jk} + BMA_{ijk} + \varepsilon_{(ijk)\ell}$$

where

$Y_{ijk\ell}$ = measured response variable

μ = overall time mean

B_i = true effect of binder type

M_j = true effect of mineral aggregate type

A_k = true effect of binder content

The other terms are the possible interaction effects between the main variables. The subscripts have the values of 1 or 2 for i and j while k and ℓ may be 1, 2 or 3.

The effect of the soaking test was determined by means of a model similar to the one used above. In this analysis the term representing binder type was replaced by one to represent the type of test used. All of the subscripts take the sample values except for ℓ. Because only two samples were tested vacuum saturated, ℓ can only have a value of 1 or 2 for this test.

The original data for these two models was tested for homogeneity of variance using the Foster-Burr Q test already described. The results of this test are shown in Table 10. All the variables except flow were homogeneous. The common logrithm was used to transform the data for the asphalt cement samples while the inverse transformation was required for the test of binder type. The data was also checked for normality by constructing a normal probability plot for each variable.

The significance of the ANOVA analysis, shown in Table 11, was checked by using the Student-Newman-Keuls test to do a multiple, pairwise comparison of all the mean values. These results will now be discussed more fully for each of the dependent variables.

Sample Density

The sample densities after curing are plotted in Figure 34 as a function of binder content. In all cases a linear trend is shown with higher binder contents resulting in higher densities. The emulsion samples aren't quite as linear as the asphalt cement samples. The increase is significant for all but the crushed limestone samples with asphalt cement binder. This causes the limestong to have an insignificant difference between the two binder types while the sand and gravel samples do have a significant difference. The higher density obtained with the asphalt cement may be partly due to the higher compaction temperature for these samples.

Table 10: Results of Phase II Homogeneity Test*

Response Variables	Analysis of Binder Type		Analysis of Test Type	
	Q Statistic	Homogeneity	Q Statistic	Homogeneity
G_W	0.185	Accept Q_1	0.210	Accept Q_1
V_A	0.164	Accept Q_1	0.209	Accept Q_1
VMA	0.187	Accept Q_1	0.208	Accept Q_1
P	0.300	Accept Q_2	0.284	Accept Q_2
F	0.475	Reject Q_2	0.477	Reject Q_2
log F	0.381	Reject Q_2	0.358	Accept Q_2
1/F	0.303	Accept Q_2		
S_m	0.289	Accept Q_2	0.244	Accept Q_1
I_m	0.208	Accept Q_1	0.179	Accept Q_1

1). $Q_{2,12,0.01} = 0.276$

2). $Q_{2,12,0.001} = 0.358$

*Both analyses contain 12 groups with 2 degrees of freedom.

Table 11: Summary of ANOVA Results
(All of Phase II)

a) Effect of Binder Type

Source of Variation	γ_W	V_A	VMA	P	F	log F	1/F	S_m	I_m
B	S-	S-	S-	NS	S-		S-	S-	S-
M	S-	S-	S-	S-	S-		S-	S-	S-
A	S-	S-	N O T S I G N I F I C A N T						
BM									S
BA				S-	S		S	S	S
MA				S+	S		S	NS	NS
BMA				S	NS		S+	NS	S+
mult.R^2	.857	.946	.909	.645	.592		.688	.539	.682

Response Variables

S- = $\alpha \leq .009$
S = $.009 < \alpha \leq .05$
S+ = $\alpha < .1$
NS = not significant

b) Effect of Test Type

Source of Variation	γ_W	V_A	VMA	P	F	log F	1/F	S_m	I_m
T	NS	NS	NS	S	NS	S+		NS	NS
M	S-	S-	S	S-	S-	S-		S	S-
A	S-	S-	NS	NS	NS	S+		S	NS
TM	S+	S+	S+	N O T S I G N F I C A N T					
MA	S	S	S						
mult.R^2	.852	.955	.914	.783	.474	.545		.396	.597

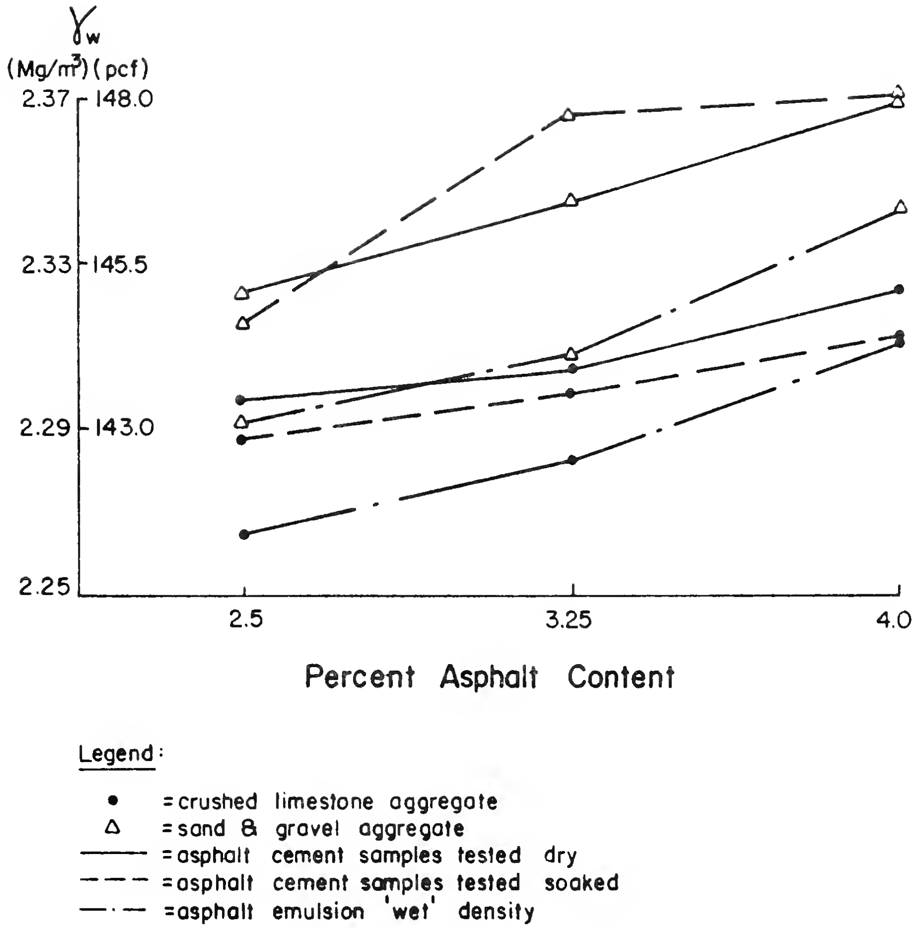

Figure 34. Sample Density as a Function of Asphalt Characteristics, Aggregate Type and Test Type

Both of the aggregate types show excellent reproducibility when asphalt cement was used as the binder. This is shown in both of the analyses as well as the average standard deviation of only 0.009 Mg/m^3. The sand and gravel aggregate obtained a higher density for both binder types, although it is only statistically significant for the asphalt cement samples. This may be attributed to the smooth, regular shape of the gravel aggregate which makes it easier for the mix to slip into the denser configuration during the compaction process.

Voids Results

The plots of air voids and voids in the mineral aggregate as a function of binder content are shown in Figure 35. The only significant variables affecting the air voids are the binder content and the aggregate type. Although the binder type did significantly affect the density, it clearly doesn't affect the air voids. The lower emulsion densities may have been partly due to the one or two percent water voids also present in these samples. This could possibly interfer with compaction of these mixes.

The asphalt emulsion samples do contain a significantly higher percentage of voids in the mineral aggregate. However these voids are constant with increased AE residue contents for all the samples. The crushed limestone had a lower density for both binder types so it would be expected to have the significantly higher void contents shown in the figure.

The variables obtained from the Marshall test will now be discussed. These are the Marshall stability, flow, stiffness and index variables discussed in Chapter 5. It should be remembered that the test was conducted at different temperatures for the two types of binders.

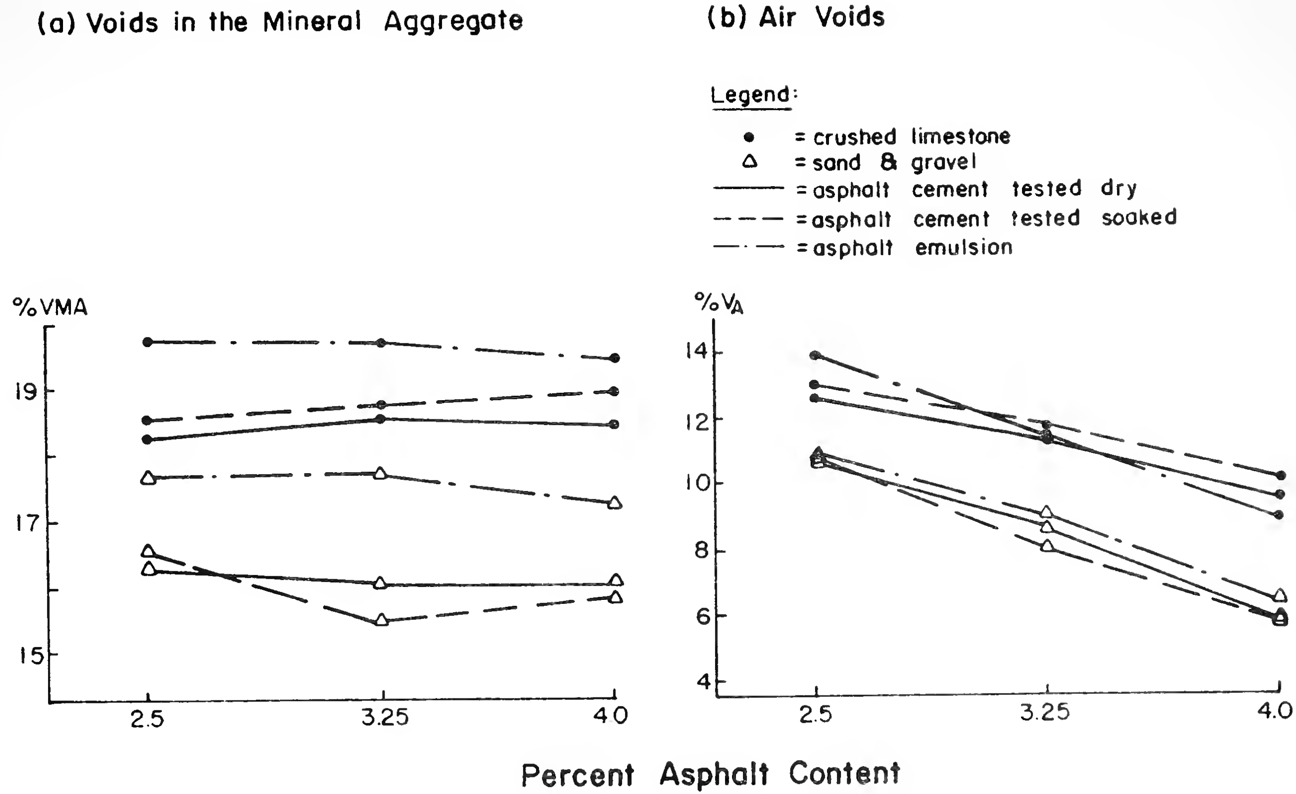

Figure 35. Air Voids and Voids in the Mineral Aggregate as a Function of Asphalt Characteristics, Aggregate Type and Test Type

Marshall Stability

The stability values don't seem to show any consistent trends between the different tests. This may be partly attributed to the variation inherent in the test itself. The analysis shows that the aggregate type is the only variable significantly affecting this parameter. In all cases the crushed limestone showed a higher stability than did the sand and gravel aggregate. It would seem that the granular interlock of the limestone, while hindering the compactability, greatly increases the Marshall stability.

None of the other variables seem to have a significant effect on this parameter. The binder content was only significant for the crushed limestone mixes with asphalt emulsion as the binder material. The high variation of these samples also causes the binder type to become significant. Although the vacuum saturated stabilities were always higher than the asphalt cement tested dry, the type of test was only significant in one case. The increase achieved by soaking ranged from 0 to 24%. Since the moisture voids only ranged between 1 and 4%, further study would be required to determine whether this increase could be attributed to some form of pore pressure. However, it is clearly apparent that the soaking was not detrimental to the stability of the asphalt cement mixes.

Marshall Flow

The results of the flow measurements are also shown in Figure 36. The factors investigated seem to have little effect on this variable. The binder content is again insignificant except for one case. The asphalt cement samples using limestone aggregate and tested dry show a sharp decrease between the 2.5% and 3.25% binder levels. However the values for samples containing 2.5% binder are very dispersed and have a standard deviation three times higher

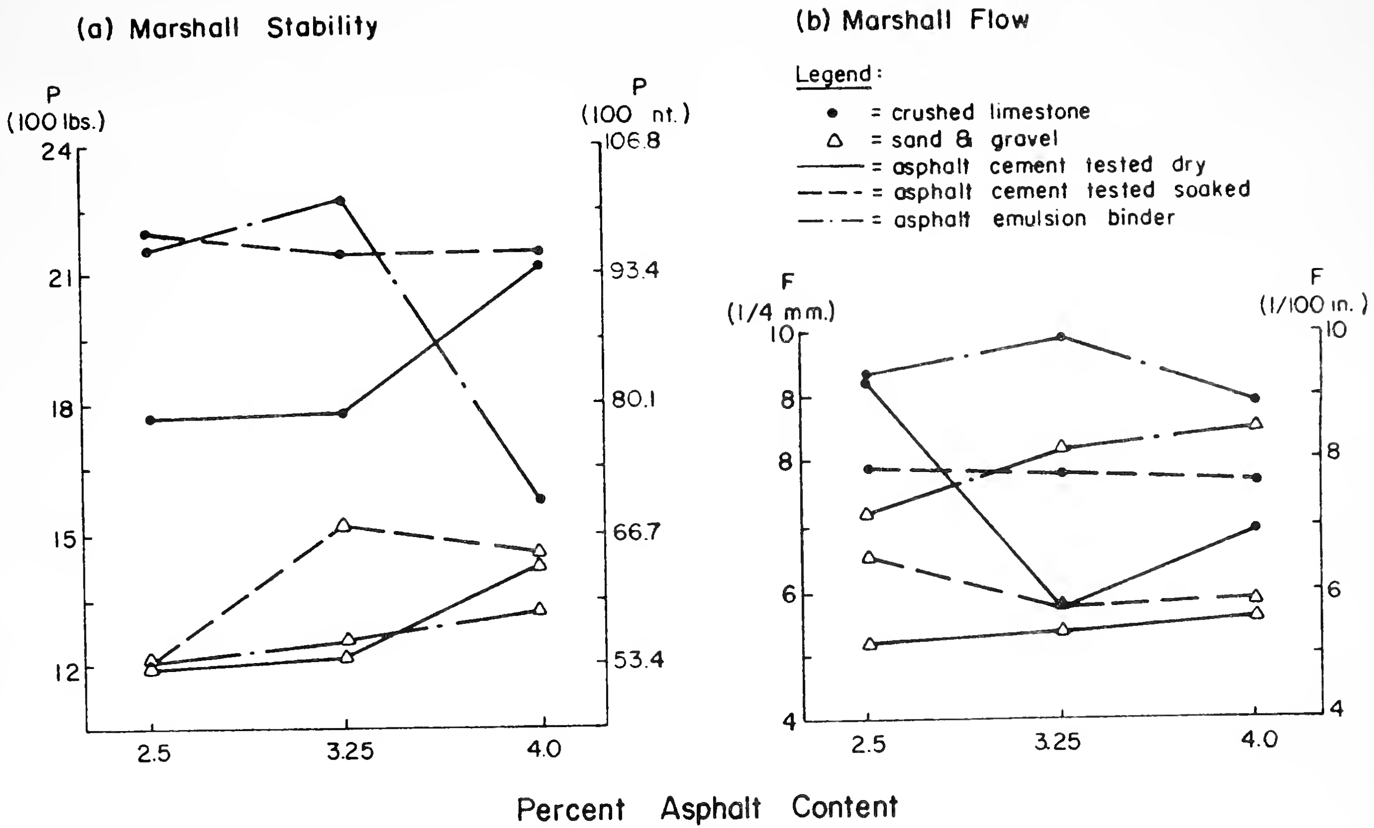

Figure 36. Marshall Stability and Flow as a Function of Asphalt Characteristics, Aggregate Type and Test Type

than the other groups. Because of this value the aggregate type is significant for this case, as well as the emulsion samples containing 3.25% AE residue. In all cases the limestone has a higher flow as a result of their higher stabilities. This mid binder level also produces the only significant difference in binder type; for the crushed limestone mixes. The type of test used for the asphalt cement samples was never significant, although the soaked values were generally higher as a result of the higher stabilities.

Marshall Stiffness

Since the stiffness variable is derived from the stability and flow values it is not surprising that the binder content doesn't affect this variable either. Only the crushed limestone aggregate with the asphalt cement binder tested dry showed a statistically significant effect of binder content. None of the other cases were significant and, as shown by the graph, the stiffness is essentially constant for the range of binder contents tested.

Neither the type of test nor the aggregate type was generally significant. Due to the higher stability values for the crushed limestone, these samples did have a slightly higher stiffness than did the sand and gravel samples. The limestone also produced the only significant difference in binder type. The samples made with the emulsion show a decrease in Marshall stiffness with increasing AE residue contents whereas the asphalt cement samples show an increase. This same pattern has already been discussed for the Marshall stability.

Marshall Index

The index values showed trends very similar to those shown by the stiffness variable. The ANOVA analysis shows

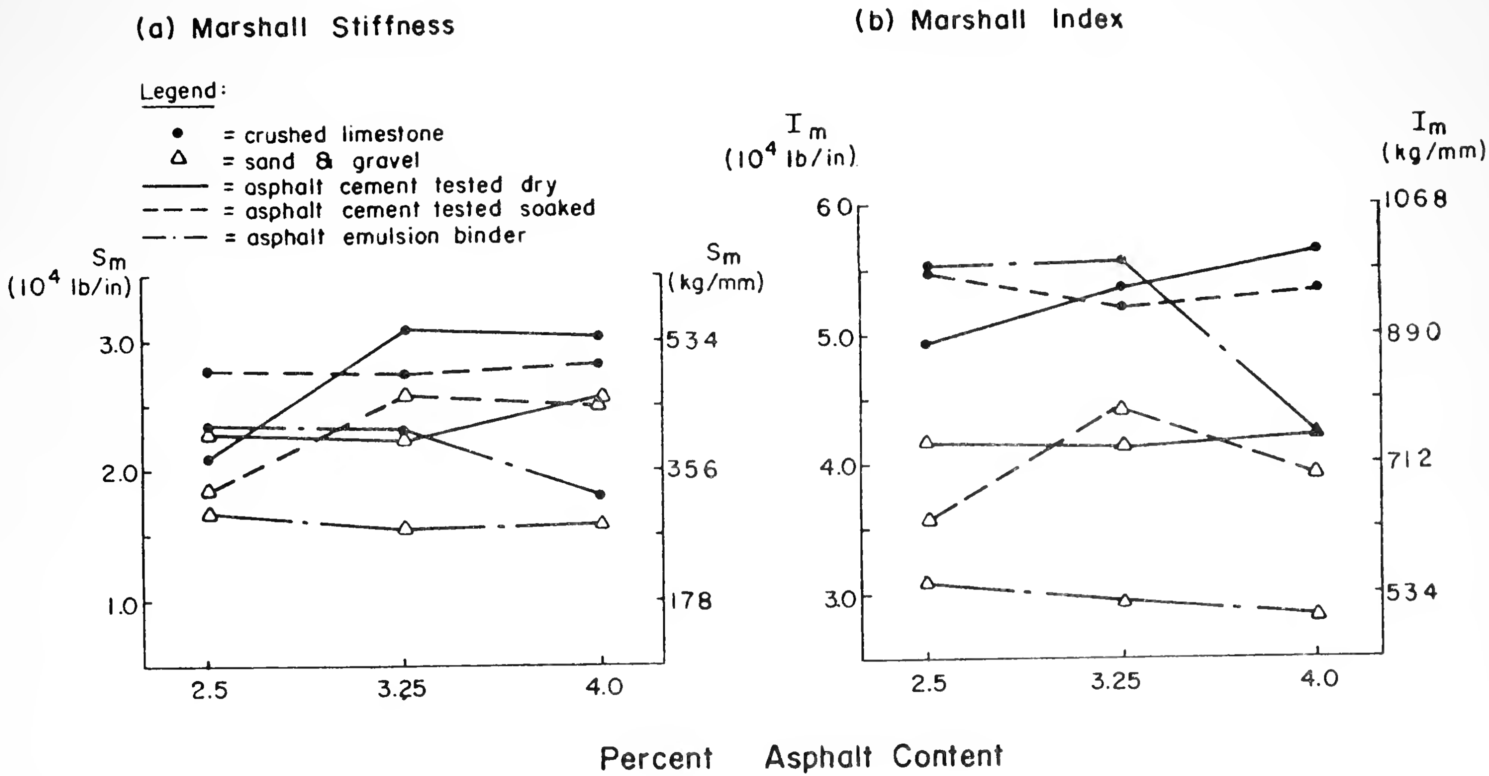

Figure 37. Marshall Stiffness and Index as a Function of Asphalt Characteristics, Aggregate Type and Test Type

that the type of test and binder content do not affect the index. The binder type was especially significant for the sand and gravel mixes. The graph shows that there is a much greater separation between the two aggregate types relative to the stiffness results. This difference is much more pronounced for the samples using the emulsion binder. The effect of aggregate type was also generally significant.

Summary

In this section the performance of mixes using 0% added moisture and asphalt emulsion binder was compared with that of the standard hot-mix samples using asphalt cement as the binder. The latter mixes were also subjected to the water sensitivity test used in the first phase of the study. Although two different mixing and testing procedures were used for the two binder types, their test results were in the same range and generally showed the same trends for both types.

The type of test used for the asphalt cement samples did not significantly affect the test results for any of the variables measured. The soaked samples generally obtained slightly higher values than did those tested dry. Only the Marshall index variable showed slightly lower values for the saturated condition.

The binder content was only generally significant for the density and air void variables. The Marshall stability for the asphalt emulsion mixes using crushed limestong was also significant.

The aggregate type had the strongest effect of all the factors tested. It was significant for all except the Marshall flow and stiffness variables. The crushed limestone aggregate has the higher value for all of the variables except sample density.

The effect of binder type, for the two test procedures used, does not show a simple trend for all of the variables measured. It is only generally significant for the Marshall flow and the voids in the mineral aggregate. The Marshall index and density variables show a significant effect for the sand and gravel mixes while the Marshall stability and stiffness variables only show a significant effect for the crushed limestone mixes. The air voids were not affected for eitherof the aggregate types.

CHAPTER 7: PHASE III: EFFECT OF AGGREGATE TOP SIZE AND SAMPLE SIZE ON AETM PROPERTIES

Introduction

This final phase of the study was a preliminary investigation of the laboratory testing of mixes containing top size aggregate greater than three quarters of an inch (1.91 cm). Since base course gradations frequently have top sizes greater than one inch (2.54 cm), the adequacy of the standard samples two and a half inches (6.35 cm) high by four inches (10.16 cm) in diameter has been questioned. The Modified Marshall method used in the previous phases was again used to test the effect of the mix parameters.

The experiment was divided into two separate sections. The first is the effect of sample size for mixes containing inch and half (3.81 cm) top size aggregate. The second section uses the standard size specimens to determine the effect of aggregate top size. The results of this latter section are presented in Chapter 8.

Experimental Design

In this phase of the study the effect of five factors was investigated. These include specimen size, aggregate top size, type of aggregate, aggregate gradation and AE residue content. The levels of the factors and the mix combination tested are shown in Figure 38. The crushed limestone and sand and gravel aggregate used in the previous section was combined with the three AE residue contents used throughout the study to form specimens with cross sections 2.5" x 4" or 3.75" x 6" (6.35x10.16 cm or 9.53x15.24 cm).

Aggregate Type	Aggregate Gradation	% Asphalt Emulsion Residue	Sample Diameter: 6 Inch		4 Inch	
		Aggregate Top Size:	1.5"	0.75"	1.5"	0.75"
LIMESTONE	F. G.	2.5				
		3.25	O		X	X
		4.0				
	M. G.	2.5	O		O	O
		3.25	O	O	X	X
		4.0	O		O	O
	C. G.	2.5	O		O	O
		3.25	O		X	X
		4.0	O		O	O
SAND & GRAVEL	F. G.	2.5				
		3.25	O		X	X
		4.0				
	M. G.	2.5	O		O	O
		3.25	O	O	X	X
		4.0	O		O	O
	C. G.	2.5	O		O	O
		3.25	O		X	X
		4.0	O		O	O

Legend:

X = 3 samples tested 'dry.'

O = 2 samples tested 'dry.'

Figure 38. Experimental Design for Phase III

The ISHC 73-B gradation specification with 1.5 inch (3.81 cm) top size aggregate was again divided into three gradations at the upper, mid and quarter points. These gradations were also scalped to three quarter inch (1.91 cm) top size (the excess being weightedly distributed over the remaining sizes) to form modified gradations conforming to the standard Marshall requirements.

Since the specimens six inches in diameter would only be required for the large size aggregates, only the midpoint gradation with 3.25% AE residue content was tested for the three quarter inch topsize gradations. Only two replicates of these large samples were tested because of the amount of material and effort involved.

Experimental Procedures

The modified Marshall method used through out the study was also used in this phase. To facilitate the construction and handling of the samples the three day, room temperature cure and the three percent added moisture levels were adopted for all samples in this part of the study.

Only slight modifications of the procedure were required for the larger specimens. To obtain densities similar to those shown by the specimens four inches in diameter, sixty-five blows of a 25 lb. (55.13 kg) hammer on each face of the specimen were required. After compaction the specimens were left in the mold for one hour before extrusion; as opposed to half an hour for the smaller specimens. The rest of the procedure was the same for all the specimens.

Statistical Analysis

The data was analyzed by the same approach applied in phase II. The ANOVA and Student-Newman-Keuls procedures were used to determine the significance of the factors tested. The original data could be tested directly, since it conformed

to the normality and homogeneity of variance requirements of the ANOVA procedure, for all but the Marshall index variable. In order to pass the Foster-Burr Q test for homogeneity of variance, a logarithmic transformation had to be applied to this variable. The results of the Q test are shown in Table 12.

The data was divided into two separate groups for the analysis. The group discussed in this chapter is the comparison of specimen size for mixes with inch and a half (3.81 cm) top size aggregate. In the next chapter the effects of aggregate top size will be evaluated for the specimens four inches (10.16 cm) in diameter.

The ANOVA model used in this section only includes second order interactions and may be represented by the following equation:

$$Y_{ijklm} = \mu + S_i + a_j + A_k + G_l + Sa_{ij} + SA_{ik}$$

$$+ SG_{il} + aA_{jk} + aG_{jl} + AG_{kl} + \varepsilon_{(ijkl)m}$$

where

Y_{ijklm} = measured or response variable

μ = overall true mean

S_i = true effect of specimen size

a_j = true effect of aggregate type

A_k = true effect of AE residue content

$\varepsilon_{(ijkl)m}$ = true random error, NID$(0,\sigma^2)$

All of these main factors are fixed and the other terms represent the second order interactions. The first two subscripts may have values of one or two; the next two may be either one, two and three and the value of m is either one or two for the six inch specimen or one, two or three for the specimens four inches in diameter.

The results of the analysis are shown in Table 13. This analysis indicates that the effect of specimen size is generally significant.

Table 12: Results of Phase III Homogeneity Test

Response Variable	44 Groups with 1 Degree of Freedom	
	Q Statistic	Homogeneity
γ_D	0.068	Accept Q_1
γ_W	0.090	Accept Q_1
WC_o	0.105	Accept Q_1
P	0.060	Accept Q_1
F	0.124	Accept Q_2
S_m	0.120	Accept Q_2
I_m	0.214	Reject Q_2
$\log I_m$	0.082	Accept Q_1
V_W	0.121	Accept Q_2
V_A	0.136	Accept Q_2
V_T	0.069	Accept Q_1
VMA	0.070	Accept Q_1

1). $Q_{1,44,0.01} = 0.111$

2). $Q_{1,44,0.001} = 0.145$

Table 13: Summary of ANOVA Results (Effect of Sample Size)

Response Variables	Source of Variation										
	S	a	A	G	Sa	SA	SG	aA	aG	AG	Mult. R^2
G_W	S-	S-	S-	S-	NS	S	NS	NS			.801
WC_o	S-	S-	S-	NS	S-	S-	S-	S-			.808
V_W	S-	S-	S-	NS	S	S	NS	S-			.802
V_A	S-	S-	S-	S	NS			S+			.901
V_T	NS	S-	S-	S-	S-		N O T S I G N I F I C A N T				.908
VMA	NS	S-	NS	S-	S-						.874
P	S-	S-	S-	S-	S-	S-		S-	S	S+	.621
F	S-	NS	NS	S+	NS	NS		NS	NS	S-	.428
S_m	NS	S	S-	S-	S	S-		S	NS	NS	.338
I_m	S	S-	S-	NS	NS	S		S	S	NS	.345
log I_m	S-	S-	S-	S	NS	S		S-	S-	NS	.483

Symbol		Symbol	
S	= sample size	S-	= $\alpha < .009$
a	= aggregate type	S	= $.009 < \alpha \leq .05$
A	= AE residue content	S+	= $\alpha \leq .1$
G	= gradation	NS	= not significant

To check the ANOVA results the Student Newman-Keuls procedure was used to do a multiple, pair-wise comparison of the sample means. The means are divided into homogeneous subsets according to a range-function dependent on the prescribed alpha level, the subset size and the degrees of freedom for the between groups run of squares.

The variables will be discussed in the same order used in the previous chapters. First the intrinsic sample characteristics will be reviewed and then the Marshall test parameters will be discussed.

Sample Density

The ANOVA analysis shows that all of the main effects are highly significant while only one of the interaction terms is significant. The sand and gravel aggregate again obtains a significantly higher density than does the crushed limestone aggregate. However, the multiple comparison of means shows that none of the factors are actually significant for the sand and gravel mixes. Only the four inch (10.16 cm) sample with inch and a half top size aggregate and the fine gradation was significantly different from the other mixes.

As was planned in the compaction procedure, the effect of specimen size on sample density is not significant for the crushed limestone mixes either. As shown in Figure 39, the six inch (15.24 cm) specimens do maintain a higher liquid content, especially at low asphalt contents. This causes the curves to shift slightly to the right. Perhaps due to the variation with only two replicates, the effect of AE residue content is also not significant for these large samples. The effect of gradation is only significant for the fine gradation which obtained an unusually low density.

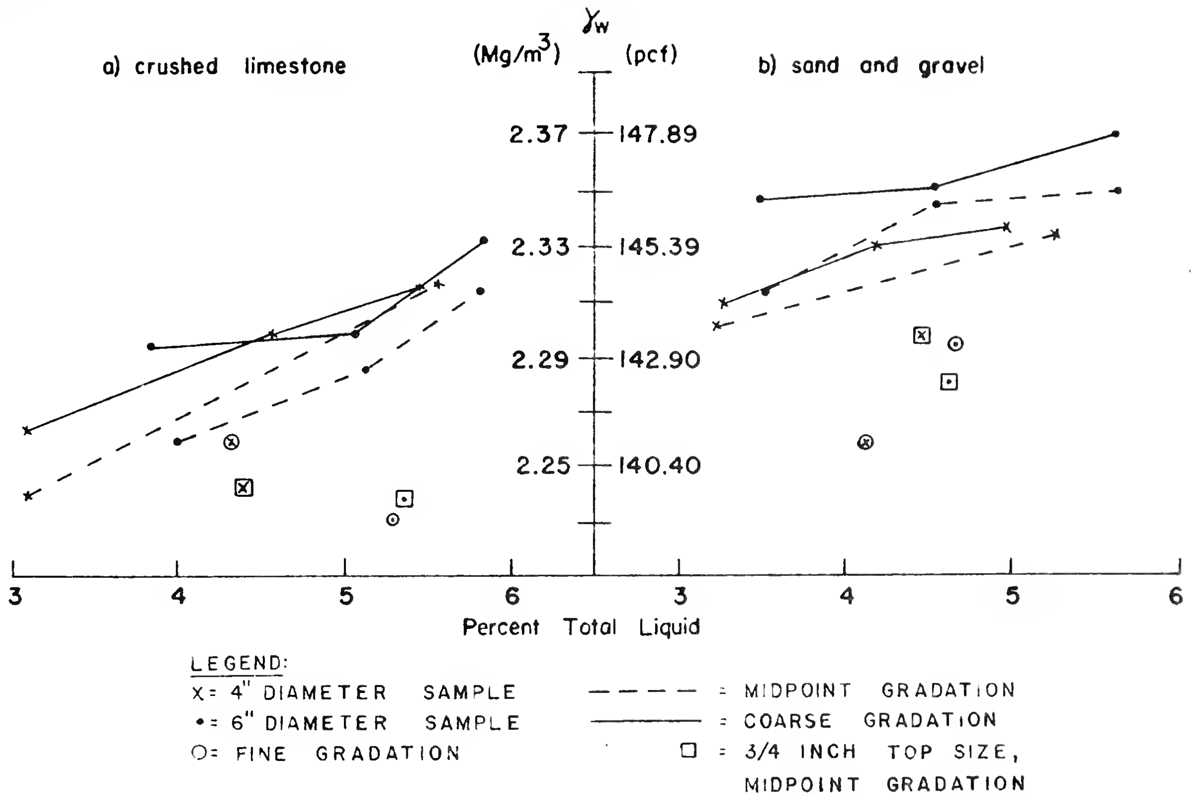

Figure 39. Sample Density as a Function of Total Liquid, Specimen Diameter and Gradation

Air Voids

The air voids have been shown to be highly correlated to sample density. As can be seen in Figure 40, their trends are simply the reverse of those for the densities. This is also seen in the ANOVA analysis with only one more term becoming significant. Moveover, the comparisons between the means show that most of the factors are generally significant for this variable.

The crushed limestone mixes will be discussed first. The effect of specimen size is significant at the 2.5% AE residue level and also for the midpoint gradation at the 3.25% AE residue level. The decrease in air voids with increased emulsion level is significant. The effect of gradation is only shown to be significant for the samples four inches (10.16 cm) in diameter.

For the sand and gravel mixes the size is not significant. The asphalt emulsion level is significant for all except the four inch specimens made with the coarse gradation. Because of the low density obtained by the four inch, fine gradation it also becomes the only significant difference for the gradation factor.

Total Voids

Because of the volume contained by the large specimens a higher percentage of the available moisture was retained, especially with the limestone aggregate. Consequently their total voids were increased to match those of the specimens four inches in diameter and the effect of specimen size was not significant, as shown by the ANOVA analysis. The effect of gradation is not generally significant. The fine gradation is significant only for the limestone samples six inches (15.24 cm) in diameter and for the sand and gravel samples four inches (10.16 cm) in diameter. The sand and gravel mixes still have a significantly lower void content than do

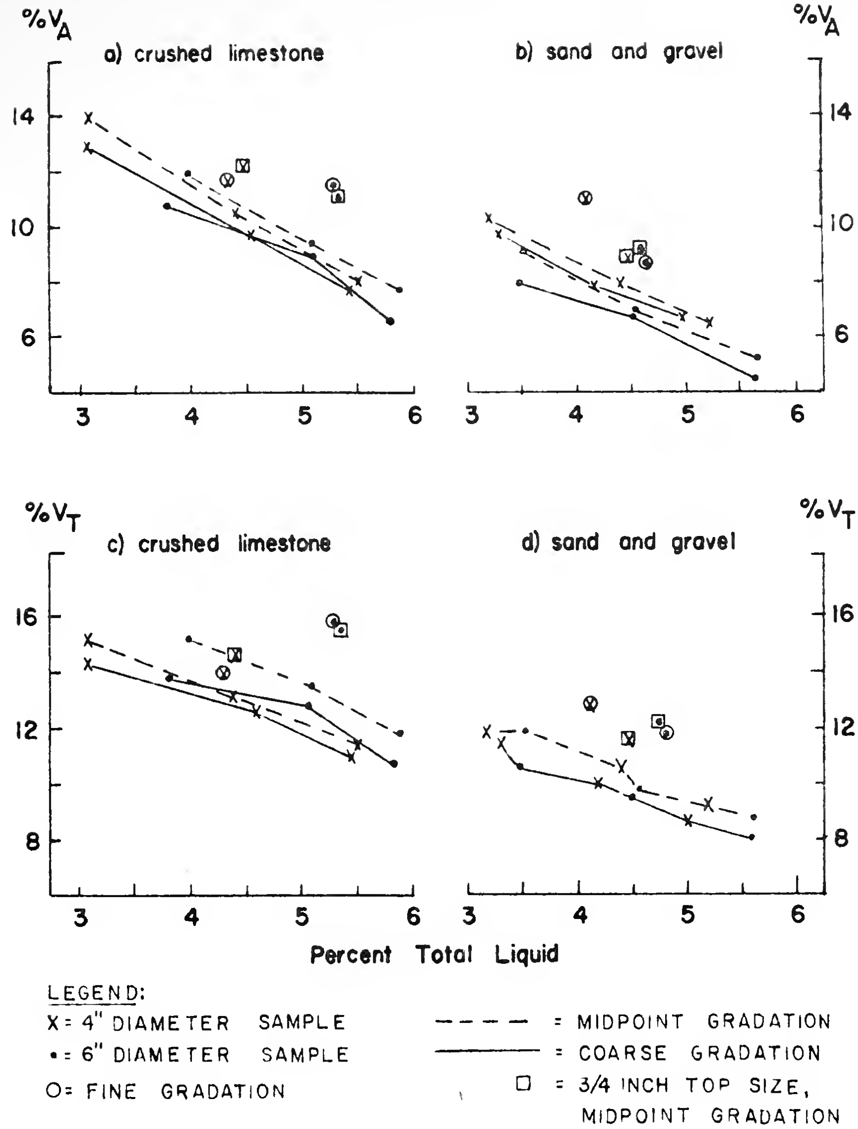

Figure 40. Air and Total Voids as a Function of Total Liquid, Specimen Diameter and Gradation

the limestone mixes. The decrease in voids with increases AE residue content is also significant for all of the mixes tested.

Percent Retained Moisture

The effect of the factors on the amount of retained moisture can be seen in Figure 41. The analysis shows the effect of gradation to be insignificant for this variable. The specimen size is generally significant for the crushed limestone but only significant for two cases with the sand and gravel aggregate. The increase in moisture with increased AE residue contents is also only significant for the crushed limestone aggregate. In spite of their lower densities, the limestone specimens seem to retain a much higher amount of moisture than do the sand and gravel specimens.

Voids in the Mineral Aggregate

The VMA have a pattern very easily described. As can be seen in Figure 41, and in the ANOVA analysis, only two factors are significant. The limestone mixes have more voids than do the sand and gravel mixes and, for each aggregate type, the fine gradation has a void content significantly higher than the others. Neither aggregate type shows any densification with increased AE residue levels. This pattern corresponds with that found in previous sections and may have been expected from the density results.

Marshall Stability

In order to 'normalize' the effect of specimen size, the stability values were divided by the maximum sample cross section before being plotted in Figure 42. It can be seen that none of the mixes show a simple, linear relationship so many of the interaction terms are significant in the ANOVA analysis.

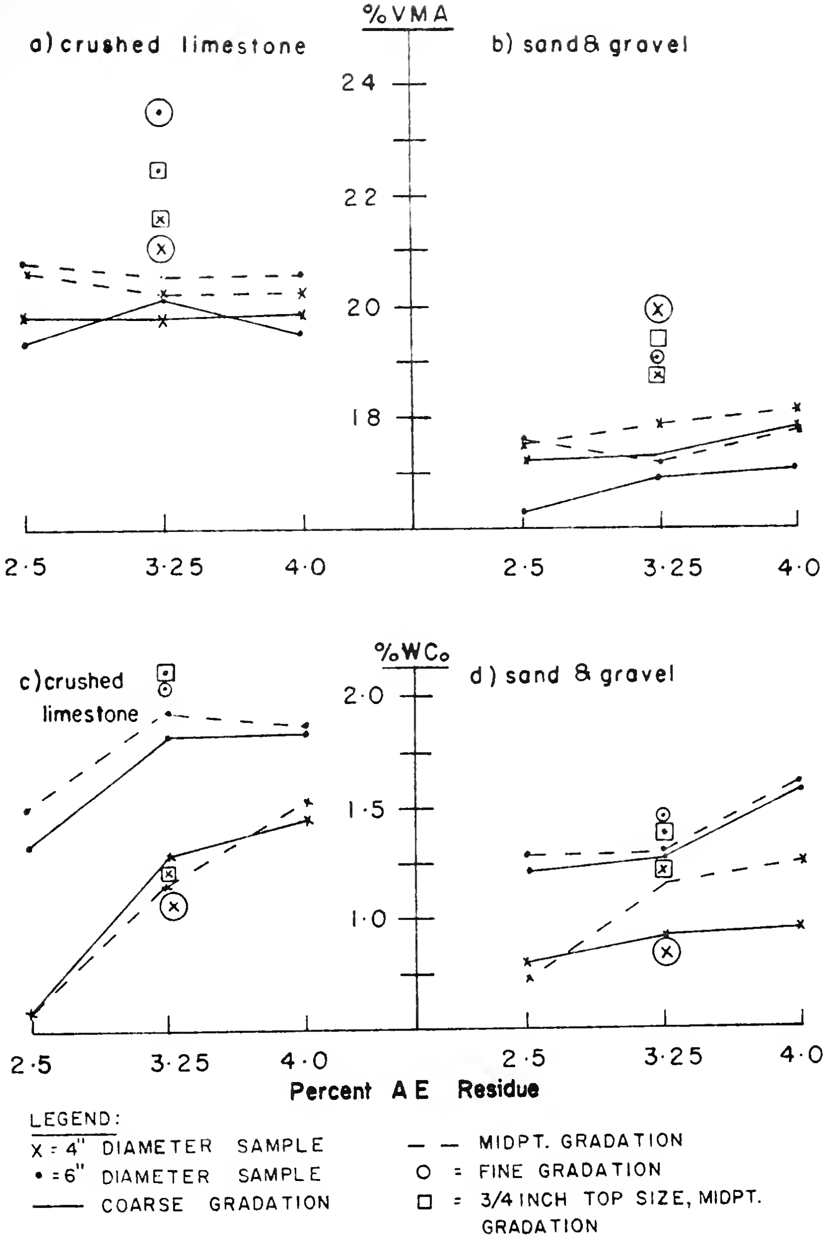

Figure 41. Retained Moisture and VMA as a Function of AE Residue, Specimen Diameter and Gradation

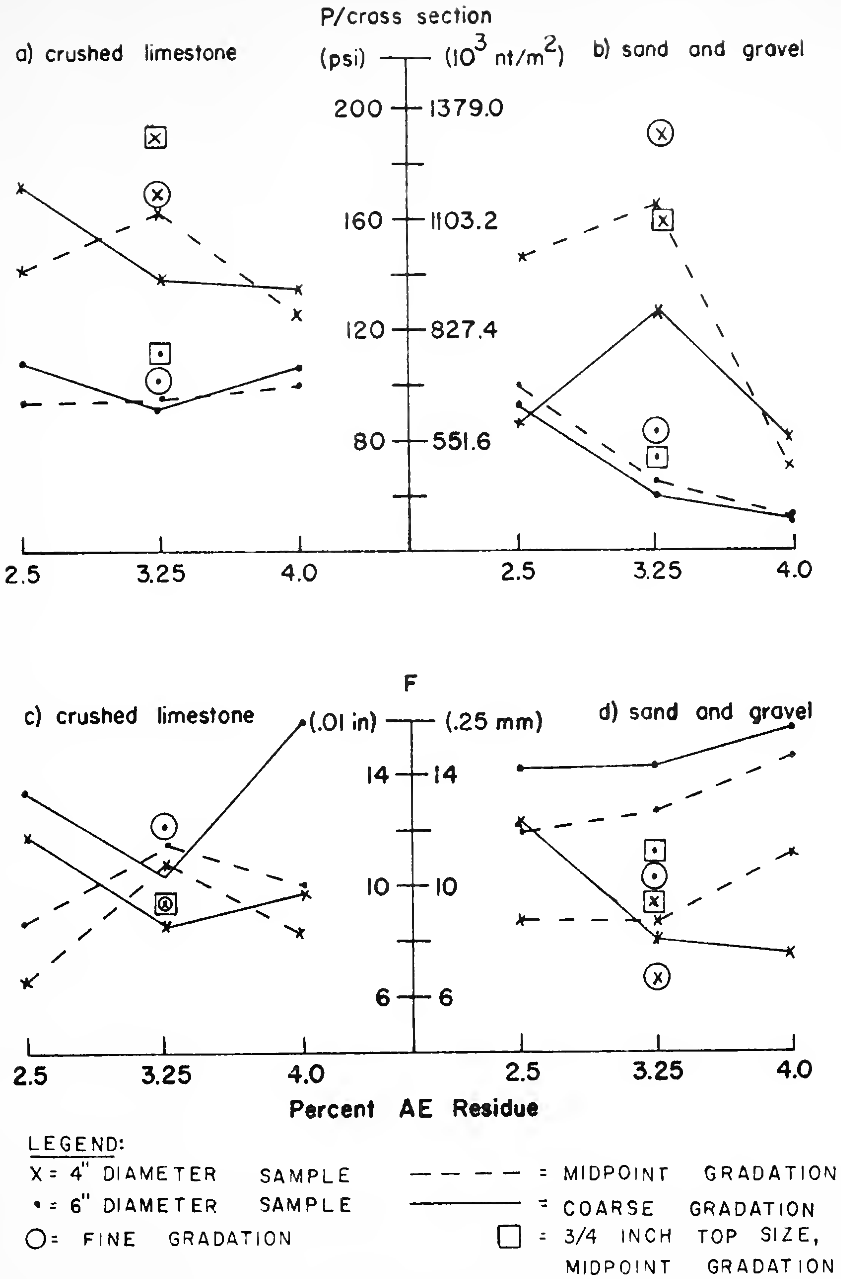

Figure 42. Marshall Stability and Flow as a Function of AE Residue, Specimen Diameter and Gradation

A different pattern is shown by each of the aggregate types. They both show a grouping of the data according to sample size. The size is significant for all but one of the limestone mixes but for only three of the sand and gravel mixes. The effect of neither AE residue content nor gradation is significant for the limestone samples. For the sand and gravel mixes the AE residue content was significant for all of the mixes. The gradation was only significant for the fine gradations and the four inch samples with the lowest AE residue content.

Marshall Flow

The flow values in this phase were not as well behaved as in the previous phases. Due to the variability among the samples, only the effect of sample size for the sand and gravel mixes attains statistical significance. Generally the two sample sizes show the same trends with the six inch samples having a slightly higher flow. This would be expected from their higher stabilities. The flow values generally decrease with the finer gradations.

Marshall Stiffness

The stiffness values are plotted against AE residue content in Figure 43. It can be seen that the stability trends are the dominant influence for the sand and gravel mixes while the flow values are more important for the limestone mixes. None of the factors have a significant effect on the stiffness values of the crushed limestone; although the same pattern is again shown by both sample sizes.

The sand and gravel mixes are all significantly affected by the AE residue content except the six inch (15.24 cm) specimens with the coarse gradation. The sample size is only significant because of the large value shown by the four inch (10.16 cm) samples with the fine gradation.

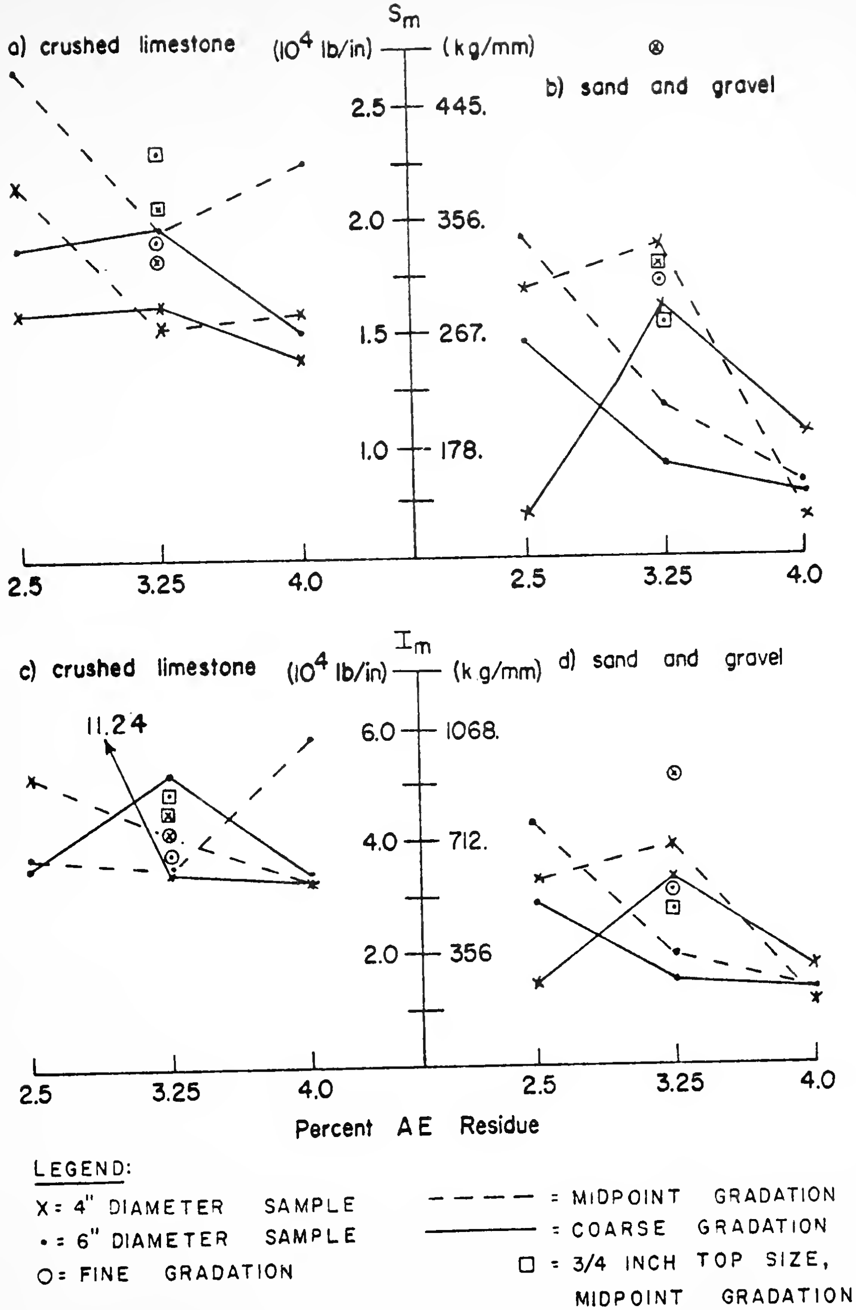

Figure 43. Marshall Stiffness and Index as a Function of AE Residue, Specimen Diameter and Gradation

The effect of gradation is also significant for these samples as well as for the four inch samples at the 2.5% AE residue level.

Marshall Index

The index values are also depicted in Figure 43. It can be seen that the index values for the sand and gravel mixes show a pattern very similar to that of the stiffness values. With the limestone mixes this is only true for the larger specimens. However, the two variables are similar that only one of the factors exerts significant influence on the limestone mixes. The ANOVA analysis shows that the limestone mixes have index values significantly higher than those for the sand and gravel mixes so the effect of aggregate type is significant.

All of the factors tested are generally significant for the sand and gravel mixes. The change in index with AE residue content is significant for all of the cases. Because of the different trends for the two sample sizes, the effect of specimen size is not significant at the 4% AE residue level and at the 2.5% AE residue level for the midpoint gradation. The four inch (10.16 cm) samples peak at the mid AE residue content while the six inch (15.24 cm) samples show a continuous decrease. The gradation is significant for all but the highest AE residue level. At this level none of the factors seem to be significant.

Summary

In this chapter the effects of aggregate type, aggregate gradation, AE residue content and most importantly, specimen size were investigated for mixes containing inch and a half top size aggregate. A summary of the analysis results will now be presented.

The most consistent factor evaluated was the effect of aggregate type. This factor was significant for all of the variables except Marshall flow. Both the Marshall stability and the Marshall flow showed the same range of values for the two aggregate types. The limestone mixes had lower densities than did the sand and gravel mixes. For all of the other variables tested, the limestone mixes obtained higher values than did the sand and gravel mixes.

The effect of specimen size is generally not significant. For the sand and gravel mixes it is only significant in two or three cases for each of the Marshall test variables and also the percent retained moisture variable. The two specimen sizes show the same trends for all except the Marshall stability, stiffness and index parameters. For the crushed limestone mixes, only the Marshall stability, percent retained moisture and air voids are significantly affected. Again the same general trend is exhibited by both specimen sizes for all of the variables except the Marshall stability and index.

The gradation also had a limited effect on the variables. For the density, voids and retained moisture variables, only the fine gradation was significantly different. Of the Marshall test variables; only the stability, stiffness and index values for the sand and gravel mixes were affected. Most of the test variables showed a ranking of their values according to gradation. The density and flow values decreased with finer gradations while the other variables showed an increase. Usually the coarse and midpoint gradations were not significantly different but with the inclusion of the fine gradation significance was achieved. It should be mentioned that the fine gradation was only tested at the mid AE residue level so no trend patterns were available for this gradation.

The effect of AE residue content differed for the two aggregate types. For the limestone mixes none of the Marshall parameters, the VMA or the six inch sample densities were affected. With the sand and gravel aggregate the AE residue content was not significant for any of the densities, the Marshall flow, VMA or the percent retained moisture.

CHAPTER 8: EFFECT OF AGGREGATE TOP-SIZE ON AETM PROPERTIES

Introduction

A more thorough investigation of the effect of aggregate top size was studied using the standard Marshall specimens four inches (10.16 cm) in diameter. In the previous chapter the effect of specimen size was shown to be generally insignificant and to modify the AETM response patterns for only the stability, stiffness and index variables. It was also observed that the effect of aggregate top size was not significant for the specimens six inches (15.24 cm) in diameter. In this chapter the effect of four factors on the AETM response variables will discussed.

Statistical Analysis

All of the four inch specimens tested in this phase of the study (see Figure 38) were used in this analysis. The four factors to be discussed include: aggregate type, aggregate top size, aggregate gradation and AE residue content. All combinations of these factors, with their various levels were tested except for the fine gradation, which was only tested at the mid AE residue level.

The data was again analyzed using the ANOVA and Student-Newman-Keuls procedures. The results of the ANOVA analysis are shown in Table 14. The second order equation used in the ANOVA analysis may be represented by:

$$Y_{ijklm} = \mu + T_i + a_j + A_k + G_l + Ta_{ij} + TA_{ik} + TG_{il}$$

$$+ aA_{jk} + aG_{jl} + AG_{kl} + \varepsilon_{(ijkl)m}$$

Table 14: Summary of ANOVA Results
(Effect of Aggregate Top-Size)

Response Variables	T	a	A	G	Ta	TA	TG	aA	aG	AG	Mult. R^2
G_W	S-	S-	S-	S-				S-	S-	NS	.819
WC_o	S	S	S-	S	S+			S-	S	NS	.689
V_W	S+	S	S-	S-	S+			S-	S	NS	.681
V_A	S-	S-	S-	S-	S+			S-	NS	NS	.898
V_T	S-	S-	S-	S-	NS	S+			S-	NS	.916
VMA	S-	S-	S+	S-	NS	S+			S-	NS	.877
P	NS	S-	S-	S-			S	S-	S-	NS	.659
F	Not Significant					S+	NS	S	S+	S-	.051
S_m	NS	S-	S-	S-				S-	S+	S+	.408
I_m	S	S-	S-	S	S+	S-		S-	S-	S+	.413
log I_m	NS	S-	S-	S				S-	S	NS	.575

Symbol

T = aggregate top size
a = aggregate type
A = AE residue content
G = gradation

Symbol

S- $\alpha < .009$
S $.009 < \alpha \leq .05$
S+ $\alpha \leq .1$
NS Not Significant

where

Y_{ijklm} = measured or response variable

μ = overall true mean

T_i = true effect of aggregate top size

a_j = true effect of aggregate type

A_k = true effect of AE residue content

G_l = true effect of gradation

$\varepsilon_{(ijkl)m}$ = true random error, NID $(0,\sigma^2)$

The subscripts of these main effect terms may take on the values of one or two for i and j and one, two or three for k, l and m. The other terms in the model are the second order interaction effects.

The ANOVA analysis indicates that all of the factors significantly affect most of the response variables. The Marshall flow variable is not affected by any of the main effects while the aggregate top size doesn't significantly affect the Marshall test results. The extent of this significance will now be discussed for each response variable.

Sample Density

The sample densities are shown in Figure 44. As in the other phases of the study, the main factor appears to be the AE residue content. All of the mixes except the sand and gravel with three quarter inch type size aggregate show near linear increases with AE residue content. However this increase is only significant for the limestone aggregate; nearly twice that shown by the sand and gravel.

The aggregate topsize was also only significant for the crushed limestone samples. The inch and a half (3.81 cm) aggregate obtained a higher density for both aggregate types but this was not significant for the sand and gravel mixes. The sand and gravel mixes also show different response

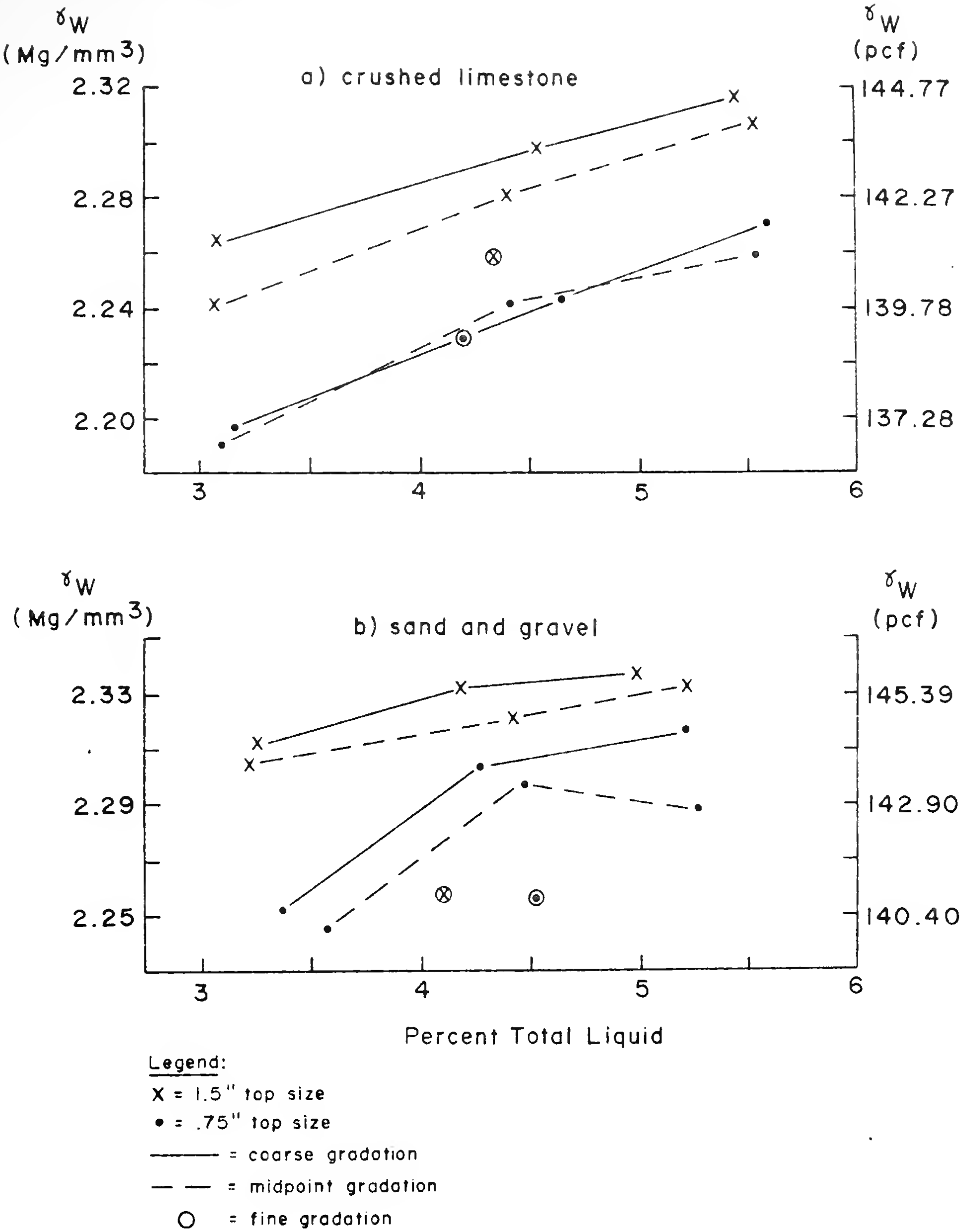

Figure 44. Sample Density for Specimens 4" in Diameter as a Function of Total Liquid and Aggregate Characteristics

patterns for the two topsizes; a slight, linear increase for the inch and a half (3.81 cm) aggregate and a peak for three quarter inch (1.91 cm) aggregate.

For both aggregate types, the only significance of gradation was for the fine gradation with inch and a half topsize. The coarse gradation obtained the highest density for each aggregate size. The midpoint gradation was slightly less dense and the gradation was the least dense. The fine gradation was considerably less dense for the sand and gravel mixes.

As in the previous two chapters, the sand and gravel aggregate achieves a higher density than does the crushed limestone aggregate. This difference is significant for the lower AE residue levels because of the different slopes shown by the two aggregate types.

Air Voids

As has been shown in previous discussions, the air voids show trends highly correlated with, and just the reverse of those for the sample densities. The results, shown in Figure 45, follow this expected pattern. The same relationships discussed for the sample densities are also applicable for this variable. In addition, the decrease in air voids with higher AE residue contents becomes significant for the sand and gravel mixes with three quarter inch (1.91 cm) topsize aggregate.

Total Voids

The total voids results, shown in Figure 45, are essentially the same as for the air voids. For this variable the effect of topsize does become significant for the sand and gravel mixes at the lowest AE residue level while becoming insignificant for the fine gradation of the limestone mixes. The effect of AE residue content becomes significant for all

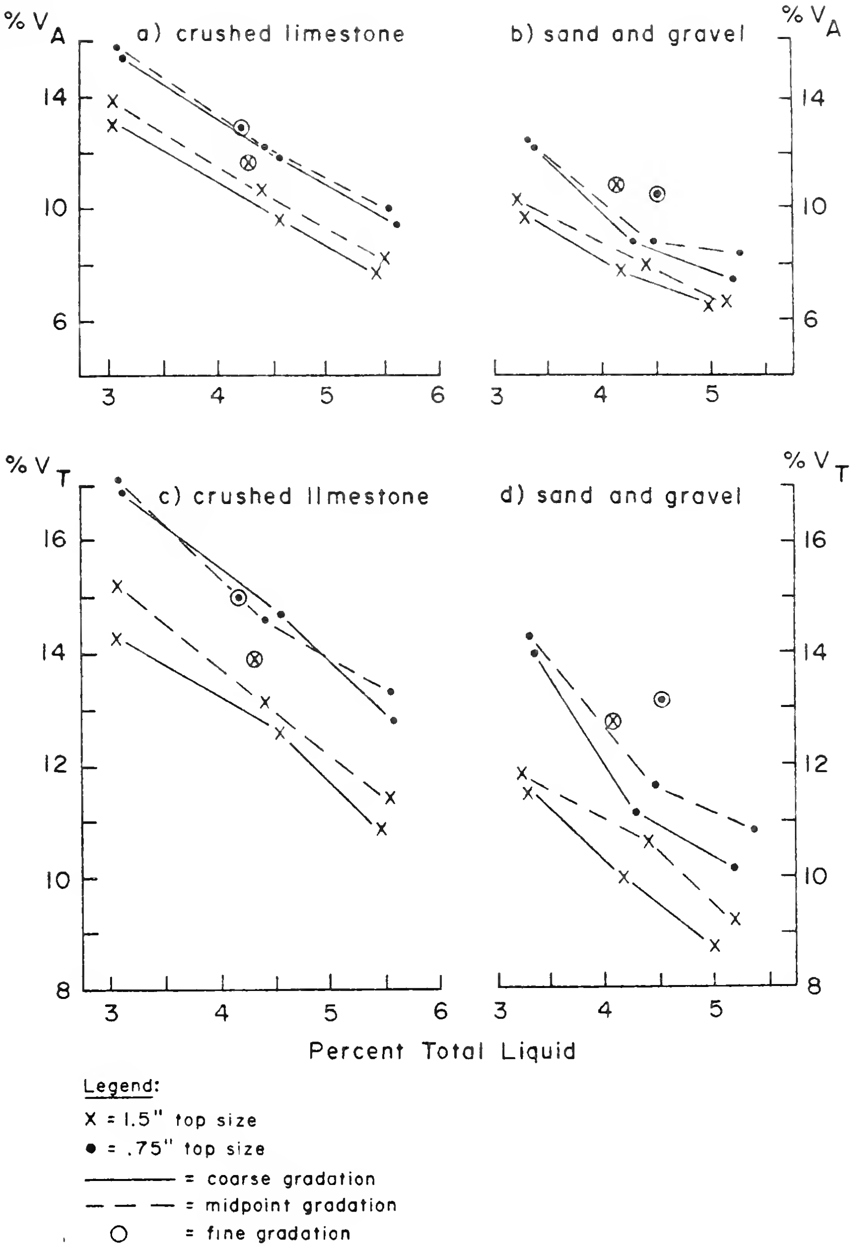

Figure 45. Air and Total Voids for Specimens 4" in Diameter as a Function of Total Liquid and Aggregate Characteristics

of the sand and gravel mixes so the decrease in voids with increased AE residue contents is generally significant. The effect of aggregate type also becomes generally significant. The gradation is still only significant for the fine gradations with inch and a half (3.81 cm) topsize.

Voids in the Mineral Aggregate

As in the other phases of the project, the AE residue content has no effect on this variable. As seen in Figure 46, these voids show very little change for the AE residue levels investigated. The aggregate topsize is only significant for the crushed limestone mixes with coarse or midpoint gradations. The effect of gradation is not generally significant although the fine gradation with one and a half inch (3.81 cm), sand and gravel aggregate does become significant. Once again the limestone voids are significantly greater than for the sand and gravel aggregate.

Retained Moisture

The percents retained moisture after curing is also shown in Figure 46. None of the factors have a significant effect for the sand and gravel aggregate while only the aggregate type and AE residue content are generally significant for the crushed limestone aggregate. The gradation is significant at the mid AE residue content where the moisture decreases slightly with the finer gradations. For the sand and gravel mixes this pattern is reversed so moisture decreases in the coarser gradation. The effect of aggregate topsize is only significant for the fine limestone mixes.

Of all the sample characteristics, the retained moisture is the only variable that showed a grouping of the data according to gradation instead of aggregate topsize. The inch and a half topsize aggregate obtained a higher density, lower voids and lower retained moisture than did the three quarter

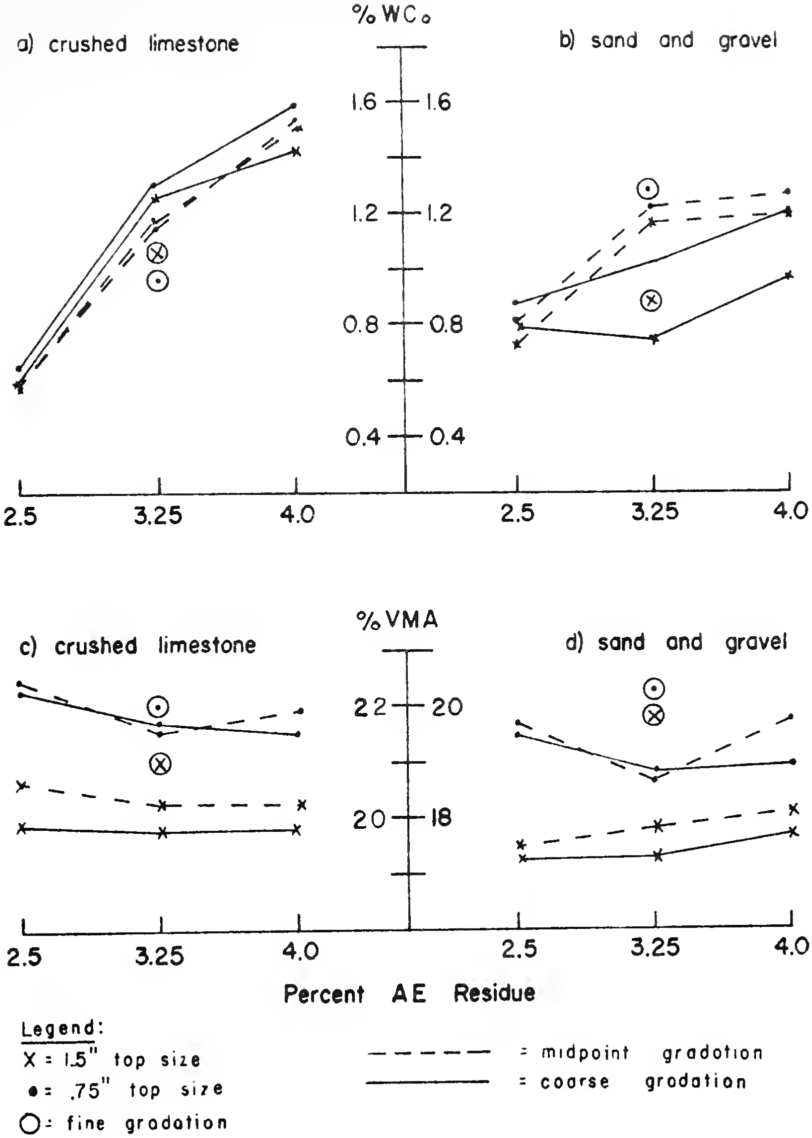

Figure 46. Retained Moisture and VMA for Specimens 4" in Diameter as a Function of %AE Residue and Aggregate Characteristics

inch aggregate. However the difference was only significant for the crushed limestone aggregate.

Marshall Stability

Both aggregate types show the same trend for the stability values. As shown in Figure 47, a peak stability is obtained at the mid AE residue level. The AE residue variable is significant for all of the mixes except those with inch and a half limestone aggregate. The sharp decrease at the 4.0% AE residue level gives this factor its significance. This pattern is not shown by the inch and a half limestone mixes. The midpoint gradation shows a symetric peak while the coarse gradation shows the decreasing pattern observed in the first phase of the study.

All of the aggregate characteristics have some effect except the aggregate top size which the ANOVA analysis shows to be insignificant. The crushed limestone mixes achieve a significantly higher stability in spite of their lower densities. The Figure shows that the stabilities are grouped according to gradation. For both aggregate types the fine gradation, with the lowest density, has the highest stability while the coarse gradation has the lowest. Once again this pattern is only statistically significant for the fine gradations with inch and a half aggregate.

Marshall Flow

The Marshall flow values are plotted in Figure 47. The limestone samples tend to show a good correlation with the stability values while the sand and gravel values are more dependent on AE residue content. Due to the variability of the data, none of the factors turned out to be significant. The crushed limestone obtains a peak flow at the mid AE residue content while the sand and gravel increases slightly with higher AE residue levels. Although the other factors don't show definitive patterns, the data is again grouped according to gradation.

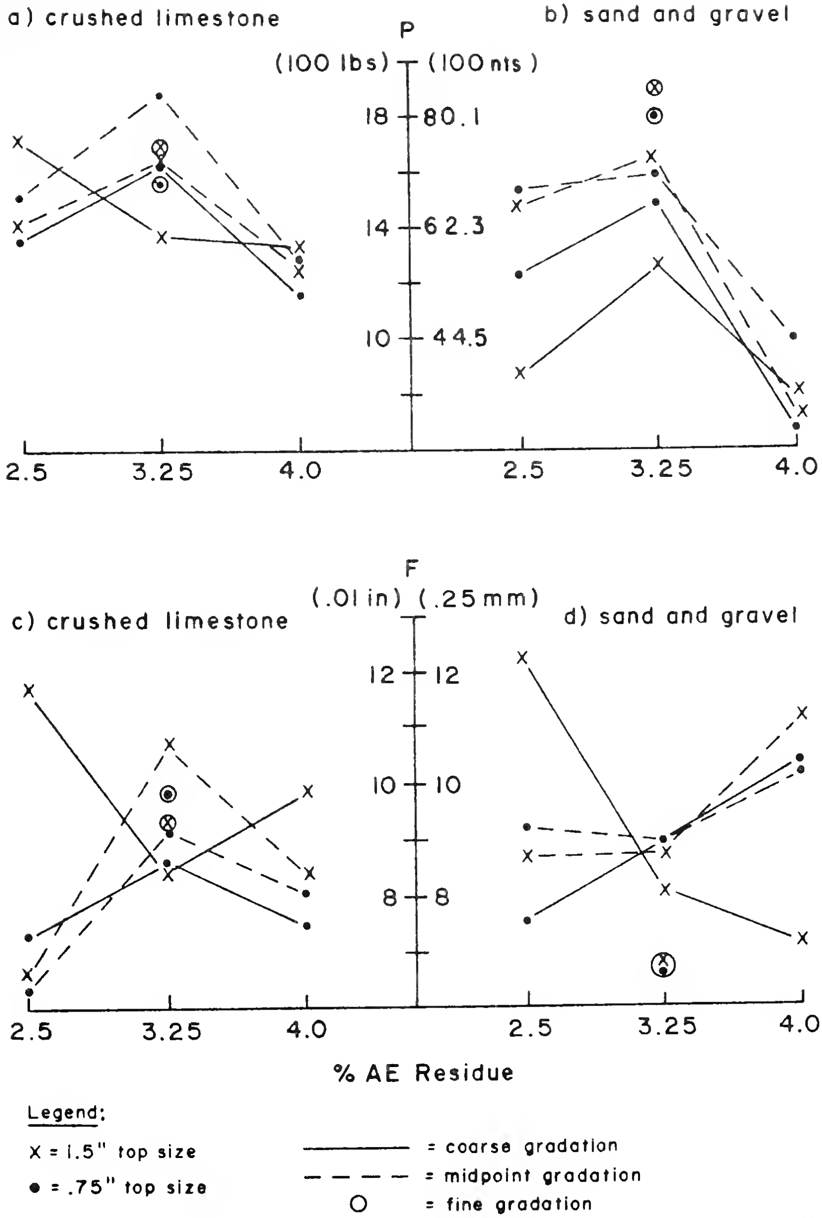

Figure 47. Marshall Stability and Flow for Specimens 4" in Diameter as a Function of %AE Residue and Aggregate Characteristics

Marshall Stiffness

The stiffness values have nearly the same range for the two aggregate types; although they show slightly differing trends as can be seen in Figure 48. Because the stability and flow values for the crushed limestone showed similar patterns, the stiffness values are fairly constant and the analysis shows that none of the factors are significant for this aggregate. The samples with sand and gravel aggregate follow the pattern established by the stability variable, i.e. an asymmetric peak at the 3.25% asphalt level.

The SNK analysis shows that the variability in flow values has also affected this variable since none of the factors are generally significant. The aggregate topsize isn't significant for any of the cases while the gradation and AE residue content are only significant for one case each. Due to the different patterns shown by the two aggregate types, this variable is significant for the two extreme AE residue levels.

Marshall Index

The index variable results show the same trends as did the stiffness values, although the pattern is slightly modified. None of the factors are significant for the limestone mixes. All of the cases form one linear line that decreases slightly with increased AE residue content. The sand and gravel mixes again show a peak value at the 3.25% AE residue level which in turn caused the AE residue factor to be generally insignificant. Contrary to the other Marshall variables, the index results seem to be grouped according to aggregate top size. This factor doesn't have any affect on the index values. The effect of gradation is only shown to be significant for the fine gradation with inch and a half topsize aggregate. However, the aggregate type is still significant with the limestone mixes displaying higher index values than do the sand and gravel mixes.

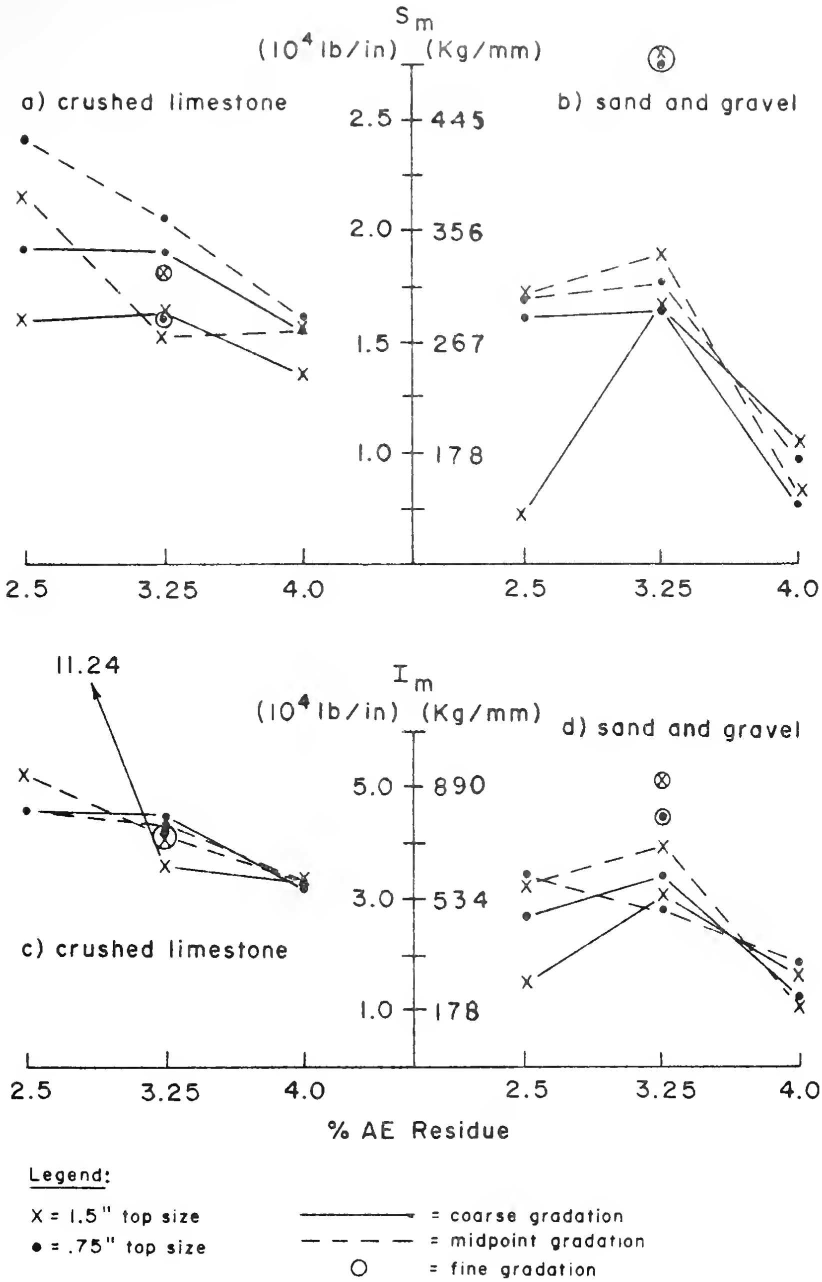

Figure 48. Marshall Stiffness and Index for Specimens 4" in Diameter as a Function of %AE Residue and Aggregate Characteristics

Summary

Two types of patterns were observed in the data results of this section. The variables representing sample density or void contents were all grouped according to aggregate top size. This causes the aggregate topsize to be significant in the ANOVA analysis. However, the SNK analysis shows that this factor is only generally significant for the crushed limestone aggregate. All of the other response variables show a grouping of the data according to gradation, so the aggregate topsize is not significant.

The effect of AE residue content is largely dependent on the other factors so no simple pattern is observed. It has a minimal effect on the flow, stiffness and VMA variables. The air voids, total voids, percent retained moisture and Marshall stability were all generally affected by the AE residue level and it was highly significant for these variables. The sample density was only significantly affected for the limestone mixes while the Marshall index was only affected for half of the sand and gravel mixes.

The remaining two factors investigated in this section showed opposite effects for the SNK analysis despite the similarity of their ANOVA results. The aggregate type was generally significant for all of the variables discussed; with the exception of Marshall flow for which none of the factors was significant. On the other hand, the aggregate gradation is only significant for the fine gradation with inch and a half topsize. The percent retained mositure showed a significant effect for all of the limestone gradations with 3.25% AE residue content.

CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

Summary of Factor Effects

The results of a detailed laboratory evaluation of asphalt emulsion treated mixtures (AETM) has been presented in this report. The effects of different aggregate types, aggregate gradations, aggregate top size, binder type, binder content, sample size, added moisture content and curing time were evaluated to determine their influence on mix properties and performance. The first two phases also included a water sensitivity test to determine the mix durability after water saturation.

The procedure and variable levels used in sample preparation or testing were developed in a previous study (18). The findings of this report should not be extrapolated to other conditions without further testing. This is important because AETM performance is dependent on a complex array of factors and factor interactions. Thus, the changing of one variable may affect several of the mix characteristics. The following is a summary of some of the findings of the study.

One of the most important factors affecting AETM performance is the amount and type of liquid present in the mix. The asphalt emulsion residue forms the largest portion of this liquid. Only 10% to 40% of the total liquid is moisture (less than 2.0% by weight of dry aggregate). This portion is dependent on asphalt emulsion content, percent added moisture, sample size and curing time. The two added moisture levels used in the first phase of the study (1.5%W and 3.0%W) had the same amount of retained moisture

after three days of air curing. It was also found that the ultimate cure (3 days at 120°F (48.9°C)) had total liquid levels similar to mixes with no added moisture and one day cure. The percent added moisture did show a small effect but it was not generally significant for any of the response variables measured.

The second phase of the study evaluated the effect of binder type and water sensitivity of the asphalt cement samples. The binder type had some significance for all of the variables except the air voids. The density and Marshall index variables were only affected for the sand and gravel mixes while the Marshall stability and stiffness were only affected for the limestone mixes. The water sensitivity test, conducted on the asphalt cement samples, only had a significant effect on the Marshall stability; with the saturated samples having higher stability values than those tested dry.

In the last two phases of the study the effect of aggregate type was investigated. This factor had the most consistent effect of all the factors investigated. The sand and gravel mixes had values less than the limestone mixes for all of the variables except sample density. This effect was significant for all of the variables except the Marshall flow values in the last phase.

In the last phase of the study the effects of sample size and aggregate top size were investigated. It was found that neither factor was generally significant. The samples were compacted to equal densities so the effect of size on density, total voids, VMA and Marshall Stiffness was not significant. The effect was significant for the Marshall stability, flow and index with the sand and gravel aggregate, and for the air voids and Marshall stability with the limestone aggregate. The aggregate top size did not affect the Marshall test variables. The samples with large

aggregate top size had a slightly coarser gradation. The specimens four inches (10.16 cm) in diameter contained 6 to 10 aggregate pieces greater than 3/4 inch (1.91 cm), while the six inch (15.24 cm) specimens contained 25 to 38 pieces. The top size was only generally significant for the total voids. The other sample characteristics (sample density, percent retained moisture, air voids and voids in the mineral aggregate) were only significantly affected for the limestone mixes.

The effect of aggregate gradation was investigated in phases one and three. In both of these sections it was observed that the gradation did have a small, although significant, effect. The significance could usually be attributed to the fine gradation which was farthest from the maximum density gradation. In the first phase the effect of aggregate gradation was only significant for the sample characteristics (density, air voids, total voids and VMA) while it was more generally significant in the last phase. This may have resulted from the use of different gradation specifications in the two phases.

The effect of sample curing was only studied in the first phase for the one day, three day and ultimate curing conditions. This factor was significant for most of the response variables and had the largest effect on the Marshall variables of all the factors in the study. In Chapter 5 the difference between one and three day curing was shown to be generally insignificant. Only the Marshall stability tested dry showed a significant difference. However the difference between the one day and ultimate curing condition was significant for all of the variables except VMA, total voids and some of the Marshall index results.

The amount of AE residue was the second variable to be generally significant. However its effect was only consistent for the variables describing the sample characteristics.

It had a large effect on all of these variables except the VMA. In the first phase of the study the residue content was significant for half of the Marshall stiffness values tested dry. The Marshall stability tested dry at the ultimate curing and the Marshall index tested dry at the higher curing levels. In the second phase it was not significant for any of the Marshall variables while in the last phase it was significant for all except the Marshall flow.

The ANOVA results show that the interactions between the main factors are most significant for the Marshall test variables. When the water sensitivity test is sued, these interaction effects were not significant. The water sensitivity test reduced the significance of curing for all of the variables except Marshall flow. The early cures retained more of their strength than did the ultimate cure. The effect of asphalt residue content was also reduced with the higher residue levels retaining more of their strength. This caused the mix to behave more like untreated aggregate with gradation being the dominant factor. The effect of added moisture was also decreased since the mixes with 1.5% added moisture had a large decrease in strength while those with 3.0% added moisture remained constant or even gained strength. As was already mentioned, the test had no effect on the asphalt cement samples.

The two new variables introduced in this study (Marshall stiffness and index) did not always show the same factor effects (especially with the ultimate curing condition) although their trends were generally similar. The testing of the samples in the saturated condition increases the similarity of the Marshall stiffness and index variables. Since the flow values were fairly constant, the stability is the most important factor affecting these variables.

Conclusions

Based on the results of the entire study utilizing the sample preparation and testing methods described in Chapter 3, the following conclusions can be postulated:

1. AETM samples tested at room temperature after one day of air curing will show stability values comparable to asphalt cement samples tested at 140°F (60°C). However, under these same conditions the AETM flow values will be nearly one and a half times those of the asphalt cement samples.
2. The testing of gradations with inch and a half (3.81 cm) aggregate top size in specimens 2.5 inches (6.35 cm) high by 4 inches (10.16 cm) in diameter generally showed trends similar to those specimens 3.75 inches (9.53 cm) high by 6 inches (15.24 cm) in diameter for the crushed limestone mixes. This would indicate that the small samples could be used for mix design of these coarse gradations. However, further testing is required since the sand and gravel mixes do not show this pattern for the Marshall variables. It was also found that scalping the gradation at the 3/4 inch (1.91 cm) sieve did not affect the test results.
3. Many of the response variables are dependent on the type and amount of liquid present in the sample. Thus the effect of the liquid portion of the mix will be dependent on all its components. In most cases these components will be asphalt emulsion residue and moisture. The effects of moisture added as part of the emulsion, added to the dry aggregate or introduced after mixing and curing (as in the water sensitivity test) will all have different effects. This requires the use of a factorial experiment to adequately portray the effect of these factors.

4. It was found that the ultimate curing condition did give results significantly different from the results of the early curing conditions. This difference could be used to establish minimum strength criteria. The way this is done would be dependent on field procedures and performance. The selection of two curing conditions should be adequate.
5. The results of this study support the conclusions of Dr. Gadallah (18) concerning the water sensitivity test. This test should be used in the evaluation of AETM. The test gives a better representation of the true effect of the factors. It also indicates the actual (inherent) mix properties under adverse conditions. A minimum "soaked" strength as well as a minimum retained strength criteria should provide adequate control of the mix performance.

Recommendations for Further Research

1. The results of this study and the study conducted by Dr. Gadallah need to be applied to a field study using standard construction procedures. This would allow the development of actual criteria for AETM.
2. The Marshall stiffness and index results need to be obtained for a wider variety of mix types. This would allow a direct comparison of the stiffness or index characterizations of the mix with the standard stability-flow criteria to determine just how sensitive these variables are and how they could be used for mix control.
3. An extension of the study to other AE residue contents (including the "optimum") would provide a better understanding of the effect of binder content on the Marshall stability, stiffness and index variables.

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APPENDIX

Table A1. Variable Ranges

		Phase I			
		%WC_o	%V_A	%V_T	%VMA
Dry Test	2.5% AE	.278-1.613	10.21-15.61	12.76-17.44	18.17-22.78
	3.25% AE	.353-1.674	8.16-13.10	10.82-15.50	18.27-22.48
	4.0% AE	.487-2.001	5.90-9.56	9.10-13.18	18.17-21.84
Soaked Test	2.5% AE	.202-1.738	11.80-18.76	14.84-19.37	20.35-24.59
	3.25% AE	.268-3.916	7.11-17.81	12.82-20.52	20.02-27.08
	4.0% AE	.602-2.126	7.09-10.53	10.68-13.33	19.58-21.97

		P	F	S_m	I_m
Dry Test	1 day cure	1196-1776	7.5-15.6	89.5-213.8	222.5-451.0
	3 day cure	1140-2272	8.2-15.8	97.4-226.6	246.0-659.0
	ult. cure	2338-3632	10.3-18.2	143.5-302.0	191.0-691.0
Soaked Test	1 day cure	1148-1508	7.9-13.1	115.7-173.4	251.2-376.8
	3 day cure	1398-1845	7.8-13.1	113.7-209.3	314.5-445.8
	ult. cure	2207-2640	9.8-14.9	160.9-220.6	390.0-530.0

Table A1. Continued

Phase II

	Asphalt Emulsion		Asphalt Cement			
	Limestone	Sand and Gravel	Limestone		Sand and Gravel	
			Dry Test	Soaked Test	Dry Test	Soaked Test
$\%WC_o$	.384 .648	.550 1.000	2.9* 5.2		1.1* 2.0	
$\%V_A$	8.81 14.25	5.96 11.23	9.03 13.27		6.53 11.03	
$\%V_T$	10.21 15.22	7.94 12.47				
%VMA	18.82 20.59	17.05 18.23	17.73 19.26		15.27 16.654	
P	1459 2435	1130 1500	1641 2356	2011 2385	1015 1468	1201 1564
F	8.6 10.7	7.0 9.5	5.1 12.5	7.0 8.4	5.0 5.9	5.8 7.1
S_m	162.1 267.2	144.0 177.0	131.3 343.3	239.4 318.0	187.9 266.9	169.2 269.5
I_m	375.5 618.0	275.0 320.0	400.0 637.5	481.0 619.0	349.0 473.0	353.0 476.5

* = % moisture absorbed in water sensitivity test.

Table A1. Continued

	Phase III			
	4" Diameter		6" Diameter	
	Limestone	Sand and Gravel	Limestone	Sand and Gravel
$\%WC_o$	.532 1.633	.700 1.575	1.235 2.110	1.149 1.672
V_A	7.37 16.12	5.42 12.73	6.61 12.26	4.31 9.93
V_T	10.77 17.29	8.47 14.52	10.40 15.91	7.85 13.09
VMA	19.34 22.64	16.23 20.29	18.59 22.86	16.23 20.19
P	1112 2089	530 2100	1800 2644	1016 2329
F	5.6 15.0	5.6 12.9	6.3 21.0	10.0 17.8
S_m	109.4 257.7	58.9 326.8	85.7 353.0	66.2 217.7
I_m	302.0 1383.0	69.0 558.0	217.0 800.0	103.0 438.0

The next four tables give the mean response value for each of the cells tested. Each of the cells is represented by a five number,coded identification. The codes vary for each of the three phases due to the changes in the factors being investigated. The explainaton of the coding for each phase is given below:

Phase I - a2bcd

a) represents the level of compacted curing and may be either 1,3 or 9

2) is a constant representing the use of no addatives

b) represents the gradation with 1 being the fine gradation and 3 being the coarse gradation

c) represents the AE residue level where 2 equals 2.5%AE, 3 equals 3.25%AE and 4 equals 4.0%AE

d) represents the amount of added moisture where 1 equals 1.5%W and 3 equals 3.0%W

Phase II - ab2cd

a) represents binder type with 5 being the asphalt cement binder and 1 being the asphalt emulsion binder

b) represents the aggregate type with 0 being the crushed limestone and 1 being the sand and gravel

2) is a constant representing the midpoint gradation

c) represents the binder content with the same levels used in phase I

d) represents the type of test where 0 represents the dry test and 1 represents the soaked(water sensitivity) test

Phase III - abcde

a) represents sample size(diameter) in inches

b) represents the aggregate top size with 3 being three quarter and 1 being one and a half inch top size

c) represents gradation with the same levels used previously

d) represents the AE levels as in Phase I

e) represents the aggregate type as in Phase II

TABLE A2.
SPECIMEN MEAN VALUES PHASE I DRY TESTS

NO	ID	GD	GW	WCO	TL	VW	VA	VT	VMA	P	F	SM	IM
1	12121.	2.220	2.194	.854	3.364	1.837	15.357	17.194	22.556	1633.5	8.2	200.6	431.5
2	12123.	2.173	2.204	1.504	4.004	3.194	14.115	17.308	22.662	1349.0	7.7	175.2	378.0
3	12221.	2.259	2.281	1.001	3.501	2.210	11.789	13.999	19.568	1625.0	9.5	171.4	397.3
4	12223.	2.271	2.302	1.394	3.894	3.095	10.459	13.554	19.151	1304.0	8.6	152.3	304.2
5	32121.	2.237	2.249	.567	3.067	1.238	13.629	14.867	20.379	1916.0	11.3	170.5	441.7
6	32123.	2.177	2.193	.753	3.253	1.603	15.540	17.142	22.507	1627.0	8.4	194.8	448.3
7	32221.	2.266	2.280	.646	3.146	1.431	12.327	13.757	19.341	2079.5	12.1	178.1	506.8
8	32223.	2.272	2.288	.713	3.213	1.583	11.947	13.531	19.129	1916.7	9.8	196.7	463.8
9	32321.	2.290	2.307	.758	3.258	1.697	11.155	12.852	18.494	1918.2	9.7	197.8	505.0
10	32323.	2.217	2.235	.835	3.335	1.811	13.816	15.626	21.089	1667.5	10.1	165.5	420.0
11	92221.	2.260	2.266	.360	2.860	.796	13.175	13.971	19.541	3260.3	12.4	263.8	340.5
12	92223.	2.260	2.267	.315	2.815	.697	13.266	13.964	19.534	3228.0	13.9	242.1	212.7
13	12131.	2.211	2.236	1.161	4.411	2.491	12.335	14.825	21.858	1772.0	9.1	195.3	414.5
14	12133.	2.203	2.234	1.484	4.734	3.172	11.982	15.154	22.160	1569.5	8.5	184.8	395.3
15	12231.	2.287	2.316	1.342	4.592	2.978	8.945	11.923	19.195	1627.7	14.1	117.7	306.2
16	12233.	2.285	2.320	1.610	4.860	3.571	8.427	11.998	19.264	1564.7	11.0	144.2	366.7
17	12331.	2.266	2.294	1.280	4.530	2.815	9.927	12.742	19.946	1653.5	10.0	167.5	437.5
18	12333.	2.255	2.290	1.600	4.850	3.503	9.638	13.141	20.312	1540.0	9.5	170.2	387.5
19	32131.	2.271	2.290	.829	4.079	1.828	10.674	12.501	19.725	2164.3	11.5	189.2	454.7
20	32133.	2.195	2.220	1.167	4.417	2.485	12.989	15.473	22.453	1578.0	10.1	156.1	359.0
21	32231.	2.298	2.322	1.043	4.293	2.327	9.135	11.463	18.773	1792.0	13.3	135.9	370.0
22	32233.	2.293	2.319	1.149	4.399	2.558	9.098	11.657	18.951	1781.0	12.4	143.6	394.5
23	32331.	2.307	2.331	1.037	4.287	2.303	9.569	11.137	18.474	1449.3	11.5	126.9	306.7
24	32333.	2.242	2.271	1.291	4.541	2.809	10.818	13.627	20.759	1544.5	10.4	149.2	339.3
25	92231.	2.291	2.299	.398	3.648	.886	10.872	11.758	19.044	3543.3	15.0	241.2	640.2
26	92233.	2.269	2.297	.373	3.623	.828	10.996	11.824	19.105	2938.7	15.1	197.0	259.3
27	12241.	2.313	2.349	1.633	5.633	3.638	6.237	9.875	18.862	1414.0	15.0	94.6	255.3
28	12243.	2.300	2.342	1.907	5.907	4.225	6.155	10.380	19.317	1412.3	12.5	113.8	254.2
29	32141.	2.300	2.328	1.272	5.272	2.817	7.566	10.383	19.320	1916.8	13.7	136.5	360.4
30	32143.	2.229	2.266	1.745	5.745	3.746	9.421	13.167	21.826	1555.0	9.9	158.5	336.5
31	32241.	2.323	2.352	1.309	5.309	2.930	6.539	9.469	18.497	1727.0	13.4	129.5	358.2
32	32243.	2.294	2.327	1.497	5.497	3.308	7.290	10.599	19.514	1547.3	14.9	110.9	303.7
33	32341.	2.313	2.343	1.341	5.341	2.988	6.870	9.858	18.847	1485.3	13.8	108.4	291.2
34	32343.	2.266	2.299	1.499	5.499	3.272	8.423	11.696	20.501	1632.5	12.6	131.9	308.3
35	92241.	2.298	2.312	.613	4.613	1.358	9.082	10.441	19.372	3227.7	16.7	193.1	502.3
36	92243.	2.304	2.321	.747	4.747	1.658	8.546	10.203	19.158	2408.0	15.5	156.2	262.3

TABLE A3.
SPECIMEN MEAN VALUES PHASE I SOAKED TESTS

NO	ID	GD	GW	WCO	TL	VW	VA	VT	VMA	P	F	SM	IM
1	12221.	2.262	2.287	1.150	3.650	2.475	13.673	16.148	21.577	1496.0	9.4	163.2	376.8
2	12223.	2.245	2.281	1.620	4.120	3.502	12.388	15.890	21.336	1148.0	8.5	135.9	324.3
3	32121.	2.234	2.249	.578	3.178	1.457	14.774	16.231	21.655	1587.5	7.9	200.9	445.8
4	32221.	2.256	2.276	.907	3.407	1.968	13.538	15.506	20.976	1516.5	9.0	169.2	394.5
5	32223.	2.231	2.250	.907	3.407	1.921	15.662	17.582	22.918	1551.0	10.0	156.8	420.8
6	32321.	2.278	2.296	.810	3.310	1.770	13.138	14.908	20.417	1532.5	7.8	209.3	512.5
7	92221.	2.225	2.231	.279	2.779	.605	14.864	15.469	20.942	2207.0	14.0	162.9	492.8
8	92223.	2.231	2.236	.269	2.769	.571	16.925	17.496	22.838	2540.3	12.7	220.6	530.7
9	12131.	2.202	2.229	1.256	4.506	2.600	15.275	17.874	24.655	1369.5	7.9	173.4	362.0
10	12133.	2.204	.045	1.948	5.198	4.010	14.292	18.302	25.048	1193.5	8.4	143.0	318.0
11	12231.	2.278	2.309	1.358	4.608	2.948	10.896	13.844	20.957	1483.5	11.4	130.2	310.3
12	12233.	2.271	2.311	1.829	5.079	3.994	9.328	13.323	20.479	1413.7	11.2	128.0	303.3
13	12331.	2.257	2.285	1.307	4.557	2.817	11.639	14.456	21.518	1316.5	9.4	140.4	334.5
14	12333.	2.247	2.290	1.938	5.188	4.168	10.462	14.630	21.679	1194.5	8.8	135.8	312.3
15	32131.	2.264	2.282	.828	4.078	1.781	12.863	14.643	21.691	1845.5	10.1	182.7	404.3
16	32133.	2.201	2.226	1.201	4.451	2.417	17.648	20.065	26.665	1684.5	9.6	176.4	410.5
17	32231.	2.269	2.293	1.126	4.376	2.421	12.181	14.602	21.653	1585.0	9.5	167.8	430.5
18	32233.	2.268	2.291	1.049	4.299	2.279	11.489	13.768	20.888	1448.0	9.7	151.3	325.8
19	32331.	2.290	2.315	1.144	4.394	2.497	10.864	13.361	20.515	1608.0	10.2	162.7	336.8
20	32333.	2.247	2.275	1.270	4.520	2.728	11.996	14.724	21.765	1398.5	9.0	157.1	345.8
21	92231.	2.271	2.277	.281	3.531	.613	12.948	13.560	20.697	2398.5	12.1	198.4	493.0
22	92233.	2.268	2.277	.408	3.658	.872	14.126	15.134	22.293	2311.7	9.8	238.4	462.3
23	12241.	2.282	2.319	1.660	5.660	3.615	8.340	11.955	20.735	1222.7	10.3	118.4	251.2
24	12243.	2.305	2.351	2.082	6.082	4.580	6.459	11.039	19.910	1506.0	13.1	115.7	278.3
25	32141.	2.302	2.332	1.340	5.340	2.928	8.653	11.581	20.398	1828.5	12.1	152.9	354.8
26	32241.	2.302	2.333	1.426	5.426	3.119	8.402	11.521	20.344	1486.5	13.1	113.7	323.5
27	32243.	2.275	2.315	1.849	5.849	3.979	8.936	12.915	21.599	1396.0	9.9	144.2	314.5
28	32341.	2.293	2.322	1.313	5.313	2.872	8.641	11.513	20.336	1516.7	12.0	139.9	349.3
29	92241.	2.299	2.315	.709	4.709	1.552	9.887	11.439	20.270	2386.5	14.9	160.9	402.0
30	92243.	2.296	2.311	.687	4.687	1.500	10.226	11.726	20.529	2433.5	14.9	163.9	390.0

TABLE A4.
SPECIMEN MEAN VALUES PHASE II

NO	ID.	GW	VA	VMA	P	F	SM	IM
01	50220	2.297	12.667	18.250	1778.7	9.3	210.3	495.0
02	50230	2.305	11.311	18.543	1786.0	5.8	308.0	536.7
03	50240	2.324	9.528	18.441	2116.7	6.9	305.8	566.7
04	51220	2.323	10.655	16.302	1197.0	5.2	230.5	419.3
05	51230	2.345	8.736	16.095	1236.0	5.5	226.0	415.7
06	51240	2.369	6.791	15.872	1431.3	5.6	254.3	423.8
07	50221	2.288	12.996	18.556	2198.0	8.0	278.7	550.0
08	50231	2.299	11.558	18.767	2141.5	7.8	274.4	523.8
09	50241	2.312	10.051	18.912	2145.5	7.7	281.4	535.8
10	51221	2.317	10.888	16.520	1202.5	6.6	184.9	357.5
11	51231	2.363	8.047	15.461	1525.5	5.8	263.0	446.3
12	51241	2.371	6.698	15.788	1466.5	5.9	250.8	394.0
13	10220	2.264	13.272	19.717	2155.7	9.4	232.2	552.8
14	10230	2.282	11.807	19.720	2270.7	9.9	230.6	557.8
15	10240	2.310	9.144	19.432	1539.3	9.0	171.8	407.5
16	11220	2.292	10.930	17.881	1203.3	7.2	168.3	310.0
17	11230	2.308	9.167	17.963	1250.0	8.1	156.7	295.0
18	11240	2.343	6.428	17.462	1320.0	8.5	155.3	288.3

TABLE A5.
SPECIMEN MEAN VALUES PHASE III DRY TESTS

NO	ID	GD	GW	WCD	TL	VW	VA	VT	VMA	P	F	SM	IM
1	43121	2.234	2.252	.875	4.125	1.910	2.095	4.004	9.509	1229.5	7.6	161.9	275.5
2	43221	2.227	2.245	.813	4.063	1.771	2.479	4.250	9.738	1541.5	9.3	170.4	340.8
3	41121	2.296	2.311	.770	4.040	1.773	9.846	1.619	7.275	870.5	12.3	71.3	151.3
4	41221	2.289	2.305	.728	3.978	1.627	.253	1.879	7.520	1430.5	8.7	171.2	334.2
5	61121	2.320	2.347	1.215	4.466	2.758	7.918	.675	5.392	2125.0	14.3	148.6	297.3
6	51221	2.286	2.315	1.273	4.528	2.855	9.123	1.978	7.512	2291.5	12.1	192.3	439.3
7	43120	2.183	2.197	.655	3.905	1.397	5.539	5.935	2.314	1355.0	7.3	197.9	450.7
8	43220	2.178	2.190	.603	3.853	1.284	5.848	7.132	2.498	1524.0	6.3	240.9	462.3
9	41120	2.251	2.264	.533	3.833	1.282	3.055	4.337	9.884	1718.5	11.5	158.9	1125.0
10	41220	2.228	2.240	.572	3.822	1.246	3.981	5.227	.716	1416.5	6.6	218.2	525.5
11	61120	2.264	2.294	1.326	4.576	2.932	.900	3.831	9.411	2413.5	13.3	187.1	351.0
12	51220	2.227	2.260	1.501	4.751	3.270	1.964	5.233	.722	2109.0	8.6	267.1	333.5
13	43130	2.215	2.243	1.315	4.565	2.826	1.876	4.703	1.746	1646.3	8.7	190.5	449.3
14	43230	2.217	2.242	1.175	4.425	2.528	2.080	4.607	1.659	1893.7	9.2	204.9	442.9
15	43330	2.209	2.229	.950	4.210	2.059	2.871	4.930	1.755	1571.3	9.9	159.0	432.5
16	41130	2.269	2.293	1.233	4.538	2.338	9.747	2.585	9.303	1336.7	8.6	162.5	359.0
17	41230	2.256	2.281	1.159	4.409	2.537	.589	3.126	.299	1645.0	10.8	153.2	420.2
18	41330	2.235	2.258	1.059	4.309	2.297	1.623	3.920	1.028	1634.0	9.3	151.9	423.0
19	63230	2.194	2.239	2.036	5.336	4.042	1.060	5.501	2.479	2450.5	10.5	231.9	455.5
20	61130	2.259	2.299	1.832	5.082	4.015	8.968	2.982	.168	2042.5	5.8	99.2	531.8
21	61230	2.245	2.287	1.852	5.112	4.059	9.418	3.477	.622	2093.3	14.7	157.7	309.7
22	61330	2.186	2.229	2.045	5.295	4.337	1.490	5.827	2.778	2302.0	12.0	192.1	378.0
23	43131	2.281	2.304	1.028	4.278	2.275	8.878	1.152	3.505	1501.0	9.0	166.9	345.7
24	43231	2.272	2.298	1.222	4.472	2.692	8.826	1.518	3.741	1505.0	9.1	178.1	247.5
25	43331	2.229	2.256	1.275	4.525	2.756	.425	3.182	.270	1795.0	6.7	275.3	452.8
26	41131	2.311	2.332	.939	4.189	2.106	7.858	9.964	7.315	1255.7	8.1	163.3	313.2
27	41231	2.295	2.321	1.157	4.417	2.608	7.982	.590	7.889	1551.3	8.9	189.6	401.5
28	41331	2.239	2.258	.855	4.106	1.863	.903	2.766	9.887	1901.7	6.8	281.6	510.2
29	63231	2.253	2.283	1.384	4.634	3.026	9.196	2.222	9.388	1672.0	10.6	159.8	283.0
30	61131	2.321	2.350	1.259	4.509	2.836	6.738	9.574	5.956	1335.5	14.6	91.7	151.5
31	61231	2.315	2.344	1.291	4.541	2.900	6.935	9.834	7.196	1453.5	12.7	114.7	204.8
32	61331	2.262	2.294	1.428	4.678	3.134	8.727	1.361	9.056	1513.5	10.4	174.4	314.8
33	43141	2.281	2.307	1.206	4.456	2.650	7.469	.118	8.982	671.5	10.4	64.5	114.0
34	43241	2.260	2.288	1.255	4.516	2.758	8.182	.939	9.723	1001.0	10.3	99.0	151.3
35	41141	2.315	2.337	.972	4.222	2.158	6.622	8.790	7.785	801.5	7.7	105.9	174.6
36	41241	2.306	2.333	1.205	4.455	2.678	5.463	9.141	3.102	715.0	11.1	68.4	114.5
37	61141	2.334	2.370	1.533	4.838	3.572	4.440	8.012	7.084	1196.0	15.8	77.4	137.0
38	61241	2.315	2.352	1.600	4.850	3.569	5.157	3.726	7.727	1202.5	14.7	82.1	134.9
39	43140	2.236	2.271	1.602	4.852	3.451	9.425	2.877	1.566	1157.5	7.6	156.2	320.5
40	43240	2.225	2.259	1.542	4.792	3.306	9.973	3.279	1.928	1291.0	8.1	161.0	334.0
41	41140	2.285	2.316	1.450	4.700	3.191	7.799	.990	9.868	1335.0	9.9	136.8	333.8
42	41240	2.274	2.237	1.523	4.778	3.334	8.078	1.412	.247	1261.0	8.4	156.6	336.5
43	61140	2.291	2.332	1.839	5.089	4.058	6.674	.732	9.634	2390.5	16.1	149.1	344.0
44	61240	2.263	2.304	1.870	5.120	4.038	7.734	1.812	.507	2232.0	10.1	226.0	591.5

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